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National Aerospace Laboratory NLR

AMS Tracker Thermal Control Subsystem

TTCS HX Structural Analysis Report

AMSTR-NLR-TN-063
ISSUE 1.0
NOVEMBER 2009

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FILENAME	AMSTR-NLR-TN-063-TTCS-HX_Structural_Analysis_report_iss01.doc	ORDER-/CODENUMBER:	2494047
LAST SAVED	2009.12.02 21:30 by J. van Es	DIVISION:	AS&A
PRINTED	2009.12.03 23:44	DISTRIBUTION:	Unlimited
PAGES	60	CLASSIFICATION TITLE:	Unclassified

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Document change log

Change Ref.	*Section(s)*	*Issue 1.0*
-	All	Initial issue

Summary

This document presents the structural analyses of the TTCS Heat eXchanger (HX). The structural analyses show all positive margins of safety for all worst cases analysed.
The case with the smallest margin of safety is the combined pressure and thermal load case. The highest stress is found in an edge of the container. This area will be constrained by an additional clip not modelled in the presented more worst case analyses. This will increase the margin. To verify the structural integrity of the design an HX burst test sample was build and successfully tested.

Contents

1 Scope

This document describes the structural analysis of the TTCS Heat eXchanger (HX). The document provides the following analyses on the Heat Exchanger assembly.

- Static Structural Analysis for launching/landing load cases
- Static Structural Analysis for in orbit load cases
- Thermal stress analysis for the critical cases in orbit
- Modal analysis
- Bolt connection analysis for launching/landing load cases
- Fail-Safe analysis for launching/landing load cases

2 References documents

Number	Title	Number	Date
RD-1	Alpha Magnetic Spectrometer-02 Structural Verification Plan for the Space Transportation System and the International Space Station	JSC-28792	March,2005

3 Introduction

The scope of this document is to verify by analysis the compliance of the Heat eXchanger sec with the structural requirements of the AMS project.

Two different configurations have been considered: Qualification and Flight Model (QM/FM) and Burst Test Sample Model (TM).

The Flight Model Model drawing packages ET6029-04 and ET6029-05 drawing packages.

The Bust Test Sample configuration is the machined product based upon the design of the Heat eXchanger (QM/FM) and can be found in drawing package ET6029-02. This Burst Test Sample is mechanical similar to the QM/FM and will be used for burst tests.

4 Heat Exchanger description

4.1 Heat Exchanger (NLR-drawings ET6029-04, ET6029-05, ET6029-02)

The Heat Exchanger is a part of the AMS-system. The function of the HX is to emit heat to a cooling system. See figure 1.

The Heat Exchanger (HX) exists of a cylindrical container and a heat exchanger inside the container. The maximum design pressure (MDP) of this pressure vessel is 160 bar.

At one side the HX will be connected with:

- the liquid pipes one comes from the PUMPS and one goes to the EVAPORATOR
- the 2 phase pipes one comes from the EVAPORATORS goes to the CONDENSERS.

The inside of the HX exists of a lot of plates foreseen with a labyrinth system to enlarge the capacity that heat can exchange.

The HX will be mounted on a base plate by means of two supports. The HX will be fixed on the support by using two clips and 4 screws per clip.

Outside the HX two THERMO HEAT WIRES are fixed by glue on the HX. The temperature of the HX will be controlled by 6 THERMAL SWITCHES, on each clip 3 thermal switches.

For the design a maximum temperature of 80 degrees Celsius has to be taken into account.

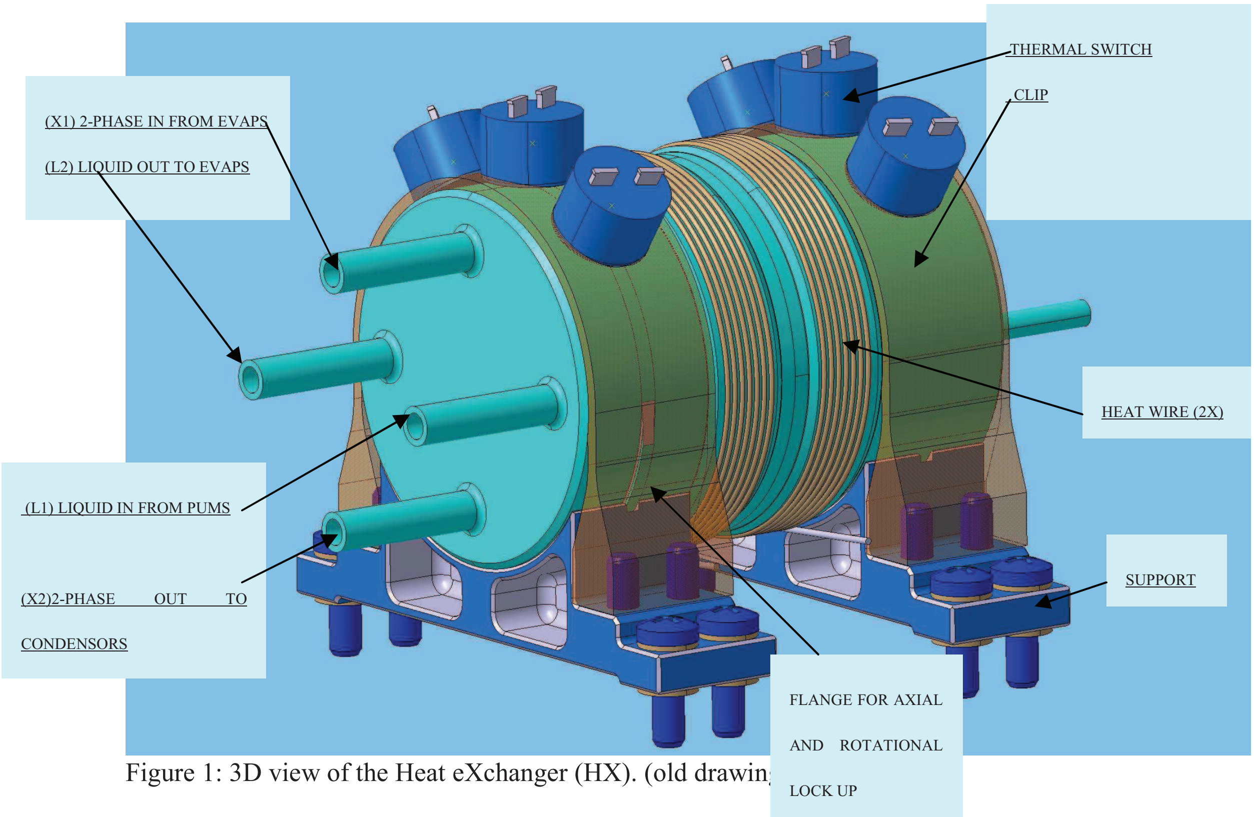


Figure 1: 3D view of the Heat eXchanger (HX). (old drawin

Figure 2 shows a drawing from a section view of the HX through the plane of symmetry. The heat exchanger core is build up by a lot of 1.5 mm plates. The orientation of the labyrinth of the disks changes every time, at the left side starting with ‘DISK1’, then followed with ‘DISK2’, and then again ‘DISK1’, etc., and ending with ‘DISK2’. A top plate makes the heat exchanger complete. This package is vacuum brazed on the left inner site of the container shell.
The axial movements of the HX are locked at the left side (see fig. 2) by means of an integral flange on the lower HX outside cylinder. This flange is placed in a groove from the left bracket. At the right side there is no flange. The HX should have the possibility to slide here.
All parts have been made of INCONEL 625, annealed condition, except all screws and the Thermo Switches. Heater wires are made of INCONEL 600 series.

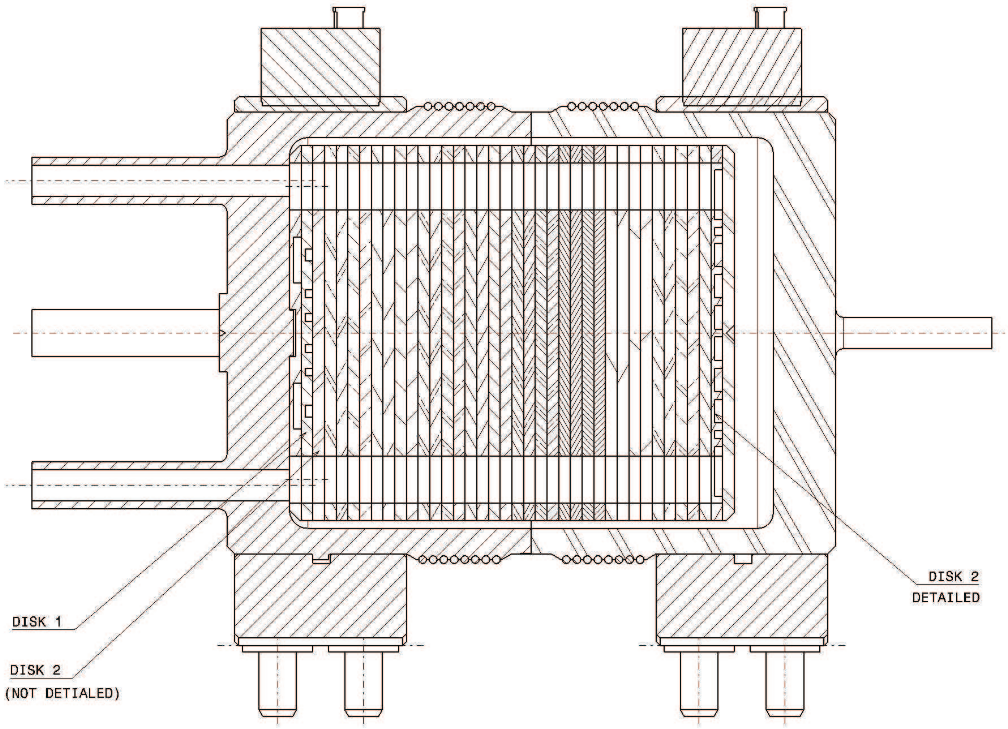


Figure 2. Section view of Heat eXchanger in plane of symmetry (drawing).

The internal maximum design pressure (MDP) is 160 bar. NLR drawings ET6029-04 & ET6029-04 show the designs of the FM primary and FM Secondary. Next Figures 3 and 4 show the HX layout and their accommodation in the Flight Configuration.

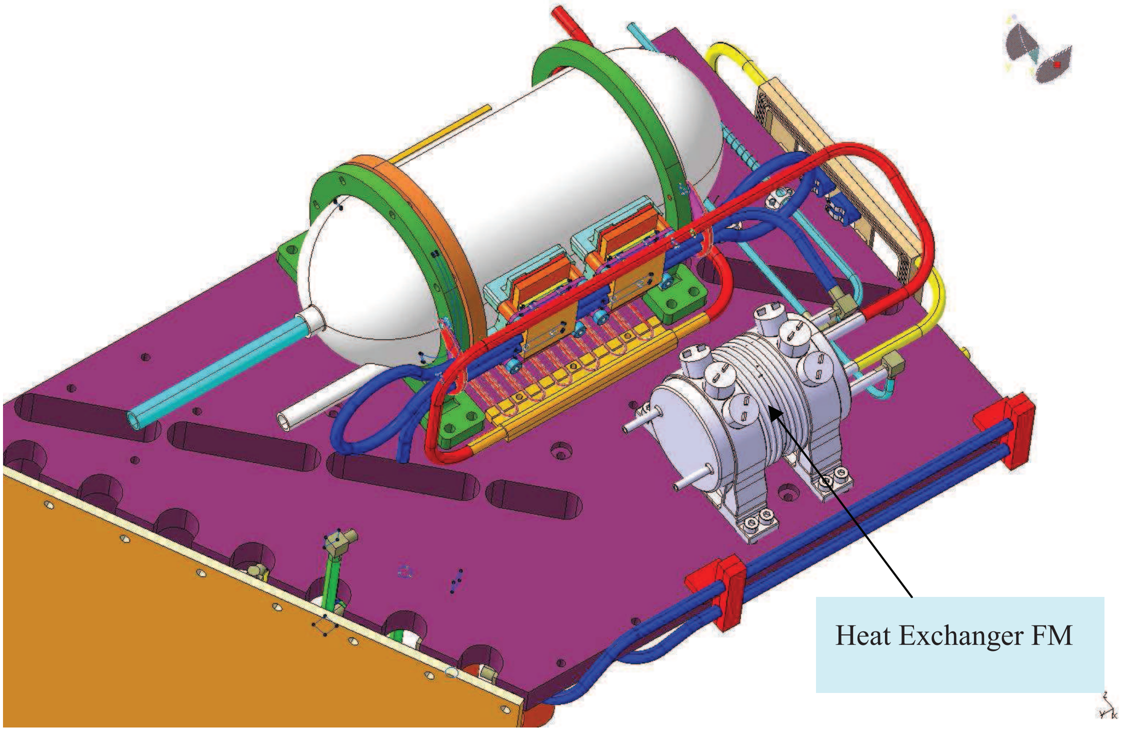


Figure 3. Heat Exchanger in AMS-03. View on pressure scanner side of HX.

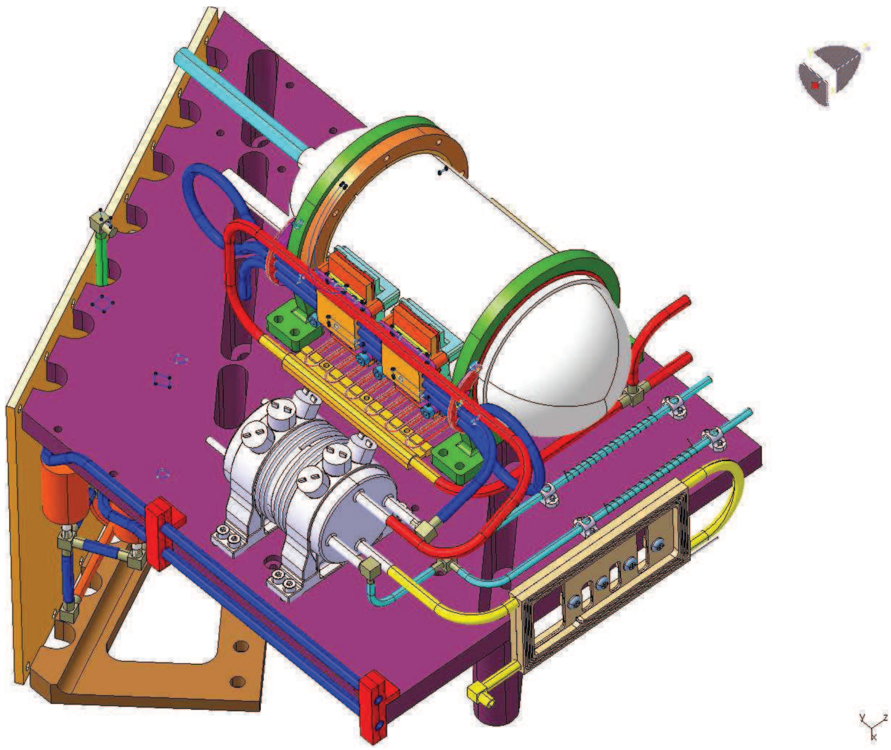


Figure 4. Heat Exchanger in AMS-03. View on connection pipes side of HX.

Heat Exchanger Burst Test Sample (NLR drawing set ET6029-02)

A Burst Test Sample been designed. This model will be manufactured to perform a burst test and verify the FM/QM concept is good.
This model will be proofed at;
- Test 1: Proof pressure of 1,5 x MDP = 1.5 x 160 = 240 bar (no plastic deformation may occur, stress < $\sigma_{0,2}$)
- Test 2: Burst pressure of 2.5 x MDP = 2.5 x 160 = 400 bar (the vessel may not show a leakage, stress < σ_{ult}).

This Burst sample is a simplified model of the QM/FM. Only the details which will play a roll in the behaviour of the QM/FM under pressure are simulated. The heat exchanger core is only simulated in the area where this core has been brazed together with the shell of the container.

Figure 5 shows a section of the HX Burst Test Model over plane of symmetry.

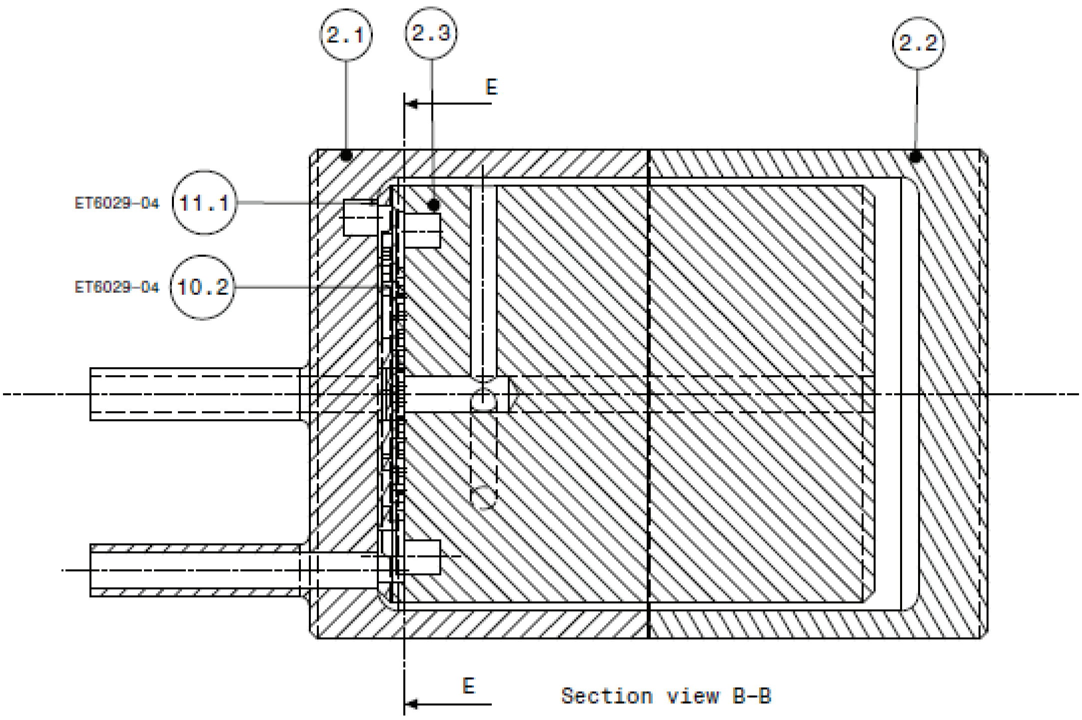


Figure 5. Section of HX Test Model over plane of symmetry.

All parts of the Test Model are made of INCONEL 625, annealed condition. NLR drawing ET6029-02-1 describes the tests which will be applied with the Test Model (Appendix A)

5 Finite Element Model description

In the following chapters the structural Finite Element Model is described.

5.1 Used Software

The software used for the Finite Element Analysis is CATIA V 5 Release 15.

5.2 Model Units

Default FEM units (otherwise specified) are:

- Length	[mm]
- Mass	[Kg]
- Forces	[N]
- Material density	[Kg/m3]
- Young's Modulus	[N/m2] is [MPa]
- Stress	[N/m2] is [MPa]
- Displacement	[mm]
- Frequency	[Hz]

5.3 Model Coordinate System

For the finite Element Model of the HX QM configuration a local coordinate system has been used. Figure 6 shows this system (white co-ordinate system).

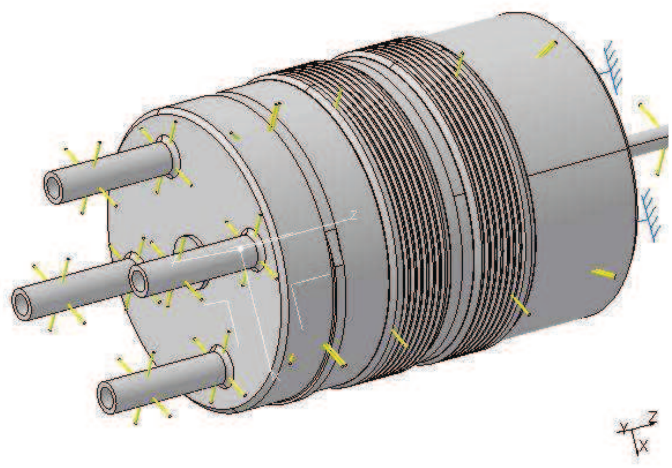


Figure 6. Local coordinate system for FE-analysis.

5.4 Model Material data

For the entire structure the used material is INCONEL 625 (sheet material for the heat exchanger plates, the clips and the brackets and bar for the container). The Finite Element Analysis is focussed on the behaviour of the container with the heat exchanger core.

In the following tables the Design Mechanical and Physical properties of INCONEL 625 (bar and sheet) are shown. The bar is used for the container the sheet is used for the HX-plates.

Material	**INCONEL 625**	
Specification	Werkstoff nr. 2.4856 ASTM B446	
Temper	Annealed	
Form	2.00" < **bar** dia. < 2.99"	
Basis	S	
	(U.S. Unit)	(SI Unit)
	ksi	N/m^2 (MPa)
Et	29.8	205471 (* 93%)
Ec	29.8	205471 (* 93%)
G	11.8	81361
F_{tu}	132	913 (* 96%)
F_{ty}	69.4	479 (* 88%)
F_{cy}	56	386
F_{bru} (e/d) = 1.5	192	1324
F_{bry} (e/d) = 1.5	88	607
μ (ν)	0.28	0.28
ρ	0.305 lb/in^3	8400 Kg/m^3
α at 20 ^oC	7e-6 in./in./F	7e-6 mm/mm/ ^oC
α at + 100 ^oC (212 F)	7.1e-6 in./in./F	7.1e-6 mm/mm/ ^oC

Table 1. Design Mechanical and Physical Properties at 20^{o}C of INCONEL 625, bar, annealed.
NB. *: Between brackets the % of the values at 20^{0}C can be used for the properties at 100^{0}C.
NB *: Values in orange rows are taken from the material CoC of the used Inconel bar (Appendix B).

Material	**INCONEL 625**	
Specification	Werkstoff nr. 2.4856 ASTM B446	
Temper	Annealed	
Form	**sheet thickness** < 0.062"	
Basis	Minimum values of A or B used	
	(U.S. Unit)	(SI Unit)
	ksi	N/m^2 (MPa)
Et	29.8	205471 (* 93 %)
Ec	29.8	205471 (* 93%)
G	11.8	81361
F_{tu}	119	821 (* 96%)
F_{ty}	56	386 (* 88%)
F_{cy}	59	407
F_{bru} (e/d) = 1.5	202	1393
F_{bry} (e/d) = 1.5	88	607
μ (ν)	0.28	0.28
α at 20 °C	7e-6 in./in./F	7e-6 mm/mm/ °C
α at + 100 °C (212 F)	7.1e-6 in./in./F	7.1e-6 mm/mm/ °C
ρ	0.305 lb/in^3	8400 Kg/m^3
SSC resistance	High	ECSS-Q-70-36A 20 January 1998

Table 2. Design Mechanical and Physical Properties of INCONEL 625, sheet < 0.062" , annealed; NB. *: Between brackets the % of the values at 20^0C can be used for the properties at 100^0C.

Material	**INCONEL 625**	
Specification	Werkstoff nr. 2.4856 ASTM B446	
Temper	Annealed	
Form	**sheet thickness** 0.251”< 1”	
Basis	S	
	(U.S. Unit)	(SI Unit)
	ksi	N/m^2 (MPa)
Et	29.8	205471 (* 93%)
Ec	29.8	205471 (*93 %)
G	11.8	81361
F_{tu}	120	827 (* 96%)
F_{ty}	60	414 (*88%)
F_{cy}	--	--
F_{bru} (e/d) = 1.5	--	--
F_{bry} (e/d) = 1.5	--	--
μ (ν)	0.28	0.28
α at 20 °C	7e-6 in./in./F	7e-6 mm/mm/ °C
α at + 100 °C (212 F)	7.1e-6 in./in./F	7.1e-6 mm/mm/ °C
ρ	0.305 lb/in^3	8400 Kg/m^3
SSC resistance	High	ECSS-Q-70-36A 20 January 1998

Table 3. Design Mechanical and Physical Properties of INCONEL 625, sheet 0.251”< 1”, annealed;

NB. *: Between brackets the % of the values at 20^0C can be used for the properties at 100^0C.

Note:

For determining the Factors of Safety the allowable stress levels for a temperature of +100 °C will be taken into account. In principle the maximum temperature of the HX will be only +65 °C.

Material	**AISI 316**	
Specification	AMS 5901/5517/5518/5902/5519 Remark: Minimum properties are mentioned below	
	(U.S. Unit)	(SI Unit)
	ksi	N/m^2 (MPa)
Et	26.0	179270 (* 88.5%)
Ec	26.0	179270 (* 88.5%)
G	10.5	72340
F_{tu}	73	503 (* 88%)
F_{ty}	26	179 (* 92%)
F_{cy}	23	158
F_{bru} (e/d) = 1.5	162	1117
F_{bry} (e/d) = 1.5	55	379
μ (ν)	0.27	0.27
α at 20 °C	8.5 e-6 in./in./F	8.5 e-6 mm/mm/°C
α at + 100 °C (212 F)	8.8 e-6 in./in./F	8.8 e-6 mm/mm/°C
ρ	0.286 lb/in^3	7916 Kg/m^3
SSC resistance	High	ECSS-Q-70-36A 20 January 1998

Table 5. Design Mechanical and Physical Properties of AISI 316, minimum properties.
NB. *: Between brackets the % of the values at 20^{0}C can be used for the properties at 100^{0}C.

5.5 Finite Element Model description

In this chapter the Finite Element Model (FE-Model) of the Heat Exchanger is presented.

5.5.1 FE-Model

The FE-model is a simplified version of the designed FM. Only the details of the FM which will play a roll in terms of stress levels, stress concentrations are simulated in the FE-Model. The difference between the HX FM and FE-model is;

The core of the HX is solid starting at the third disk at the left side from figure 2 (DISK 2 (not detailed) from figure 2) until the end plate at the right side of DISK 2 (detailed) from figure 2.

Figure 7 shows the FE-Model.

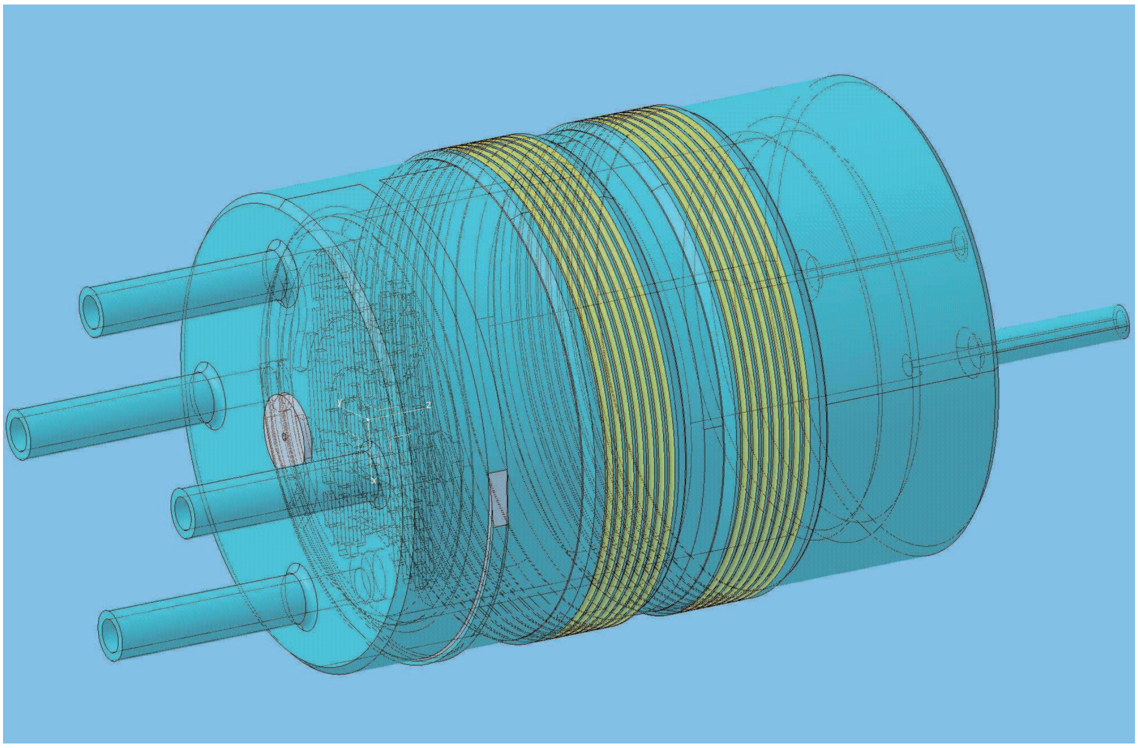


Figure 7. FE-Model. Core of HX FM heat exchanger is not detailed. The plates at the side where the heat exchanger has been brazed at the inner side of the shell is detailed for the FE-model.

This FE-Model will be used for;

1) Linear static calculations,

2) Frequency calculations and

3) Acceleration calculations.

5.5.2 Model Boundary conditions (restrains)

Figure 8 shows the boundary condition. The face at the outer side has been clamped at the side where the pressure scanners will be connected (2 tubes). This clamp restrain will influence the results where the highest stresses will occur minimal.

The influence of the absence of the two HX clamps with the support is minimal and will lower the maximum stresses, so these parts are not modelled.

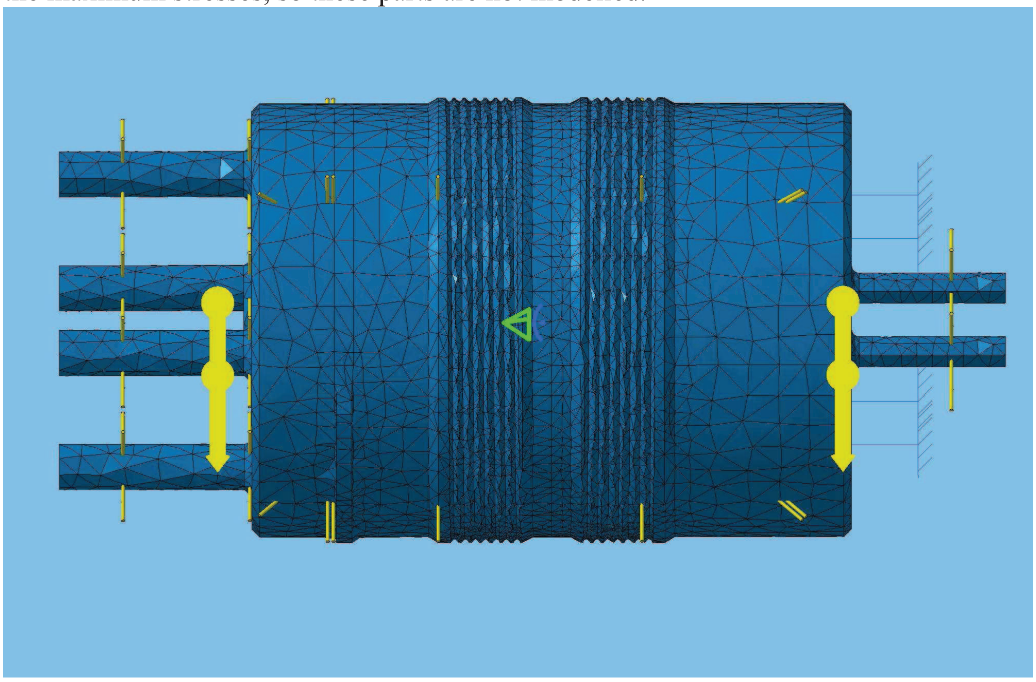


Figure 8. Loads and constrains of FE-model (side view).

5.5.3 FE-Model loads

Three load cases have been analysed:

1) Load case for Static analyses: an internal pressure of 16 MPa (160 bar) has been applied on all internal surfaces of the HX (including 6 tubes).

Figure 9 shows the internal pressure (yellow arrows).

2) FE-Model for Frequency analyses

3) FE-Model for Acceleration analyses: this load contains an acceleration vector of 42.43 g (40 g in X-direction, 10 g in Y-direction and 10 g in Z-direction). This vector has been placed perpendicular to the centreline of the HX.

Figure 8 shows the acceleration vector by means of the thick arrow ending with a bullet.

5.5.4 FE-Model mesh results

The auto mesh function of CATIA V5 has been used.

Parabolic Tetrahedron elements (TE10) are used for the model and for the all load cases.

The results convergences when the element size is 4 mm (sag = 0.6 mm).

MODEL SUMMARY	
GRID POINTS (NODES)	95012
PARABOLIC TETRAHEDRON ELEMENTS	55616

See figure 9 for a presentation of mesh results for the static calculation model.

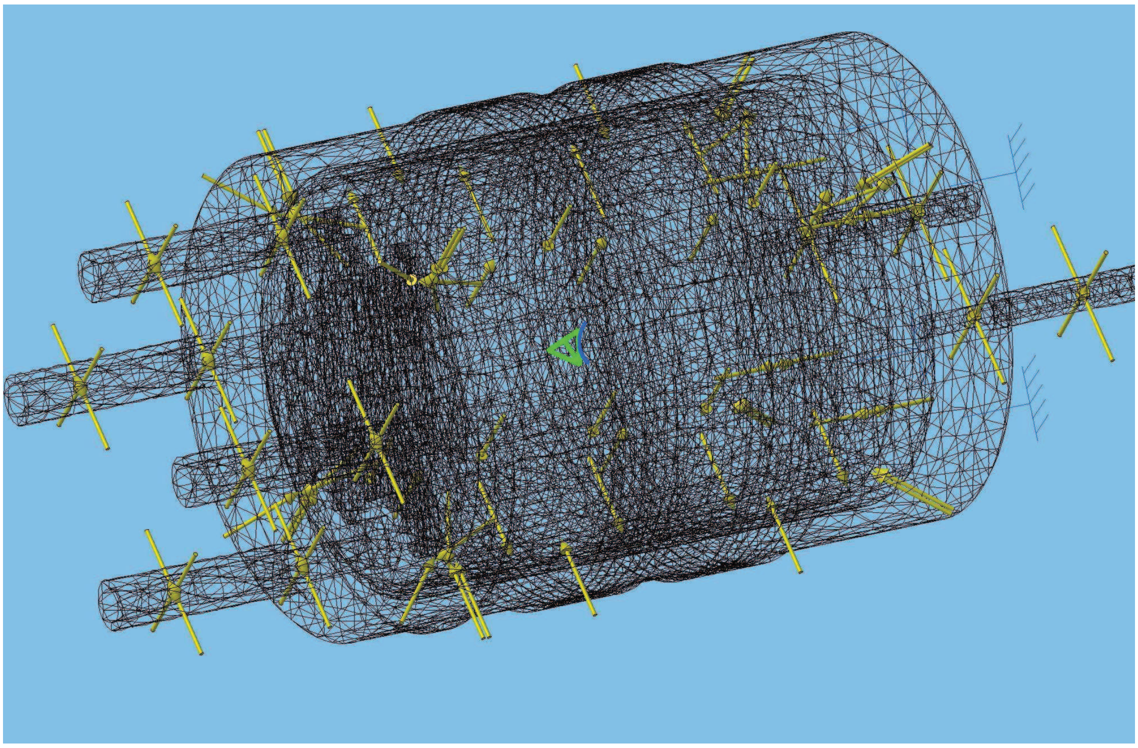


Figure 9. Elements (black lines), Loads (yellow arrows) and restrain (blue base lines).

5.6 Model check

5.6.1 Material properties.

Table 6 shows the used material properties for the elements for all analysis (see 4.8.2).

Material	INCONEL 625
Young Modulus	204100MPa
Poisson Ratio	0,3
Density	8000kg_m3
Thermal Expansion	1,28e-005_Kdeg
Yield Strength	382MPa

Table 6. Used material properties.

5.6.2 Model for Static and Acceleration analysis

5.6.2.1 Equilibrium

Table 7 shows the applied loads due to the internal pressure of 16 MPa (160 bar), the reactions and residual loads.

Components	Applied Forces	Reactions	Residual	Relative Magnitude Error
Fx (N)	-9.5592e+002	9.5592e+002	-9.3223e-011	6.4630e-013
Fy (N)	-6.3302e+001	6.3302e+001	-1.3401e-010	9.2905e-013
Fz (N)	-2.7531e+003	2.7531e+003	1.4957e-009	1.0369e-011
Mx (Nxm)	1.0017e+000	-1.0017e+000	6.5741e-012	5.1792e-013
My (Nxm)	-3.8562e+001	3.8562e+001	1.6918e-011	1.3328e-012
Mz (Nxm)	2.0123e-001	-2.0123e-001	-5.7785e-012	4.5524e-013

Table 7. Equilibrium overview.

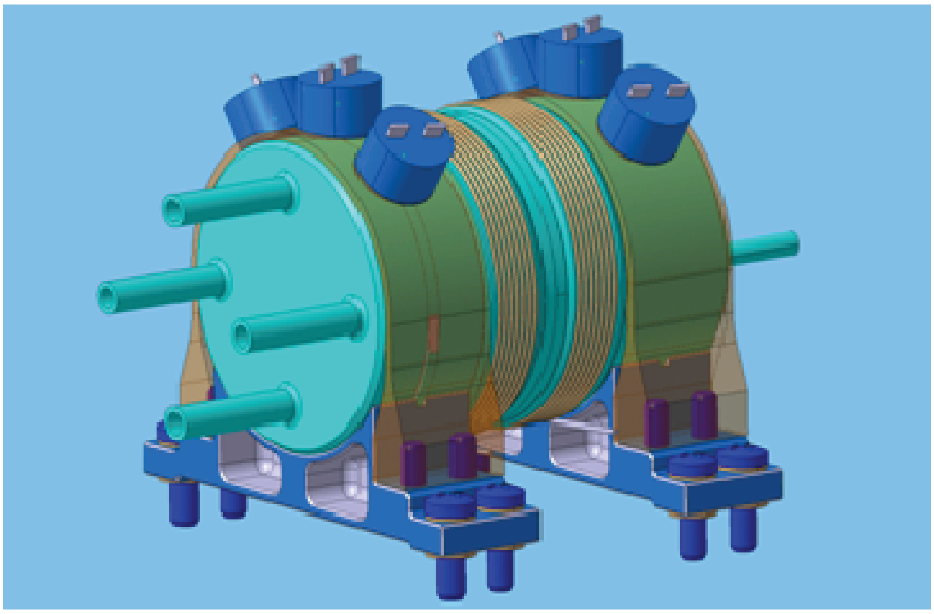
5.6.3 Model for Frequency analysis

The size of the automatically meshed tetrahedron elements is 4.14 mm:

Entity	Size
Nodes	90721
Elements	53484

5.7 Mass budget

The mass of several parts belonging to the HX and the support of this are listed below in table 5.



Component	Volume [m^3] Per part	Density [Kg/m^3]	Mass [Kg] total
HX interior	7.0748 e-5	8400	0.5943
HX container	7.7860 e-5	8400	0.6540
HX 100% filled with CO_2	5.0246 e-5	1032	0.0541
Clip (2x)	1.0320 e-5	8400	0.1734
Bracket (2X)	1.4555 e-5	8400	0.2444
Heat wire (2X)	1.0450 e-6	5000 (estimated)	0.0105
Screw bracket / base plate (8X)	4.6050 e-7	8220	0.0303
Screw clip on bracket (8X)	3.3430 e-7	8220	0.0220
Washer (16X)	2.6520 e-10	7916	3.3591 e-5
Temp.Switch (6X)	-	-	0.0480

Table 5. Mass of HX parts.

Mass HX including 100 % filled with CO_2: 1.8243 Kg.

Mass HX exclusive CO_2: 1.7702 Kg.

6 Structural requirements

6.1 Structural verification

The requirements for structural verification are specified in the RD 1. A small relevant summary is given below.

6.2 Natural frequency requirement

The first mode natural frequency of the HX structure should be above 50 Hz.

6.3 Strength requirement

The Margins of Safety (MoS) should be zero or positive, under the applicable design loads.

6.4 Safety Factors and margins of safety

The following SF need need to be applied for the TTCS Heat Exchanger. The TTCS HX is part of a pressurised system.

Safety Factor	Yield	Ultimate
Pressurised flight systems (large diameter)	1.5	2.5

Table 7. Safety Factors for structure

Tha Margins of Safety (MoS) for the structural analyses are defined as:

$$MoS_Y = \frac{\sigma_Y}{SF_Y \cdot \sigma_{load}} - 1.0$$ For the yield strength and

$$MoS_U = \frac{\sigma_U}{SF_U \cdot \sigma_{load}} - 1.0$$ For the ultimate strength where:

- σ_y the yield strength of the material
- σ_u the ultimate strength of the material
- SF_y the safety factor for yield strength
- SF_u the safety factor for ultimate strength
- σ_{Load} the maximum Von Mises equivalent stress due to external loads.

The MoS for stresses indicates the amount by which the allowable stress, defined by the material characteristics, exceeds the actual stress due to the applied loads, taking into account the applicable SF. All MoS should be positive for all load cases, for all structural elements.

7 Load Cases

7.1 Acceleration loads

The HX is a secondary structure with a mass lower than 20 pounds (9.1 kg). A primary load factor of 40 g should be applied in any axis with a load factor of 25% of the primary load to the two remaining orthogonal axis, simultaneously. For all types of calculations the most critical situation will be analysed.

The worst case is a launch load of 42.43 g acceleration perpendicular to the centreline of the HX. This acceleration of 42.43 g is the result of the vector calculation of three acceleration values: 40 g in one axis and 10 g in both other orthogonal axis.

7.2 On Orbit thermal loads

The highest thermal load on orbit on the HX structural is a safety case in which both start-up wire heaters are switched. The structure is protected against overheating by 3 thermostats in each of the two redundant heater circuits (see RD-2). The highest induced temperature profile is found just before both heaters are switched off by the thermostats.

The temperature distribution in the heat exchanger as calculated with SINDA and is used as input of the Thermal Mechanical Stress Analyses.

The temperature distribution resulting from thermal analysis and used as input for the thermal stress analysis is seen in Figure 9-3.

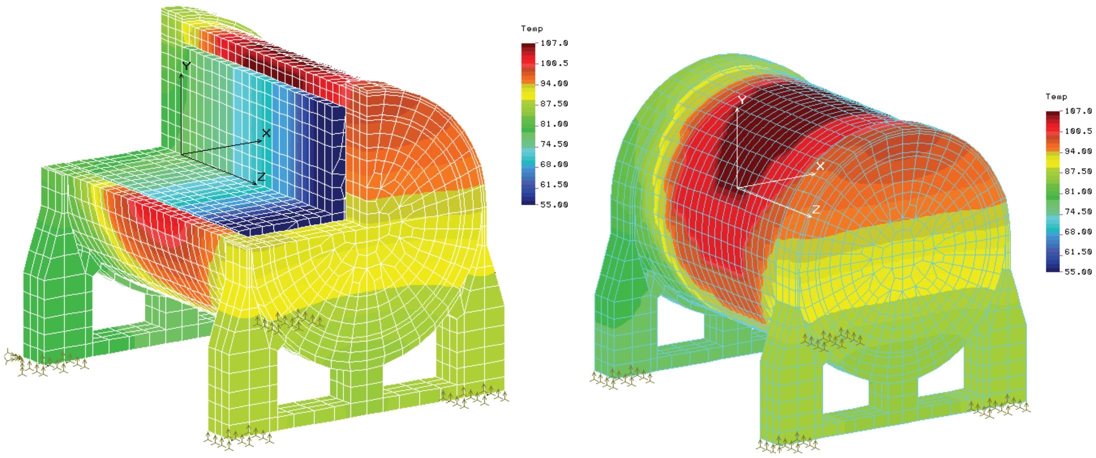


Figure 7-1: Temperature distribution in the heat exchanger due to heater failure

The mechanical model of the heat exchanger used for the thermal stress calculation is a reduced model of the model used for the mechanical (pressure and acceleration load).

7.3 Pressure loads

The TTCS Maximum Design Pressure (DP) is 160 bar (16 MPa) as explained in AMSTR-NLR-TN-044 TTCS Safety Approach.

7.4 Combined loads

When the different loads are combined the Margins of Safety (MoS) are calculated as follows:

$$MoS_Y = \frac{\sigma_Y}{(FoS_{Y1} \cdot \sigma_{\max 1}) + (FoS_{Y2} \cdot \sigma_{\max 2})} - 1.0$$ For the yield strength and

$$MoS_U = \frac{\sigma_U}{(FoS_{U1} \cdot \sigma_{\max 1}) + (FoS_{U2} \cdot \sigma_{\max 2})} - 1.0$$ For the ultimate strength where:

Numbers 1 and 2 represent the two combined load cases.

The Von Mises Stress is calculated through the following formulas:

$$\sigma_{vm} = \sqrt{\frac{\left[(\sigma_x - \sigma_y)^2 + (\sigma_x - \sigma_z)^2 + (\sigma_y - \sigma_z)^2\right]}{2} + 3 \cdot \left[\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2\right]}$$

$$\sigma_{vm} = \sqrt{\frac{\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right]}{2}}$$

The following load combinations are analysed:

1. Launch environment
    a. Combinations of acceleration and pressure
2. In orbit worst case analyses
    a. Combinations of pressure and thermal loads

The launch environment can not induce additional thermal loads as TTCS in unpowered. The pressure is induced during launch is by an induced maximum uniform temperature of 65 C.
In orbit the thermal loads are combined with the maximum pressure load.
Remark: For all calculations the material strength properties at the worst case temperature 100 C are used.

8 HX Dynamic Analysis

8.1 Dynamic analysis of FE-model

The results of the Finite Element analysis of the FE-Model (See figure 7 and 8) are shown in table 8. The first 10 modes are shown only.

Mode number	Frequency Hz	Stability
1	5.1304e+003	3.1413e-008
2	5.3051e+003	3.0075e-008
3	7.1769e+003	5.9691e-006
4	7.1931e+003	6.6262e-006
5	7.2481e+003	1.0163e-005
6	7.2811e+003	1.6125e-005
7	7.3045e+003	1.1860e-005
8	7.3166e+003	3.2472e-005
9	7.6462e+003	1.2583e-005
10	7.8069e+003	1.3969e-005

Table 8. First 10 modes of the FE-Model.

Figure 10 shows the first mode of the HX structure. The first natural frequency is 5130.4 Hz much larger than the minimum allowed 50 Hz requirement.

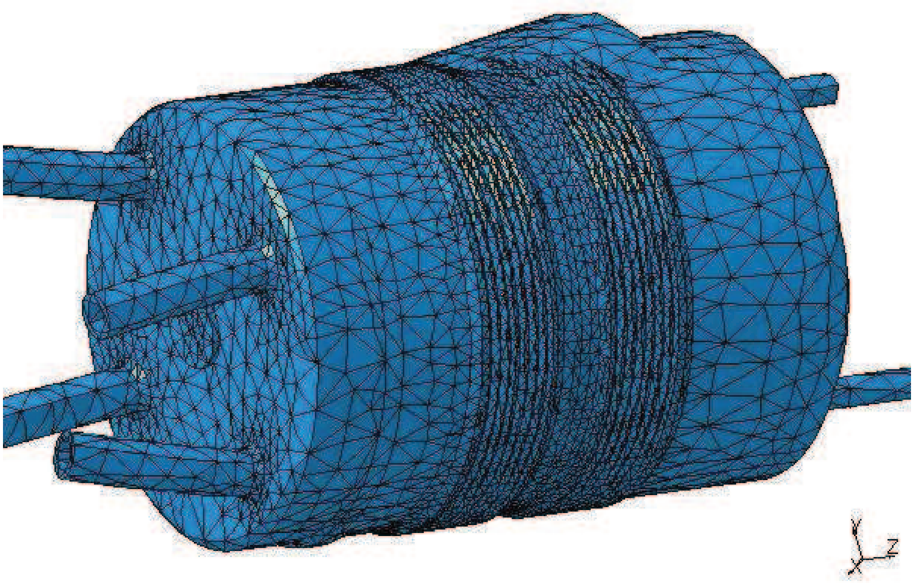


Figure 10. First mode (5130.4 Hz) of the FE-Model.

8.2 Vibration testing

The TTCS Heat Exchanger will be subjected to a vibration test on box level when integrated in the TTCB.

9 HX Static analyses

The analyses have been done for the HX FM excluding clip and support. The results show the worst cases only. First the respective displacement results are presented followed by the stress results. Stress calculations are presented for pressure and acceleration separate and combined.
For the thermal stresses a separate model has been used including clips. These stresses are shown separately and combined with the pressure load stresses. All cases are summarised in a table at the end of this section.

9.1 Static displacement results Flight Model (FM)

Next displacements of the Heat Exchanger FM have been analysed:

a) displacements from the HX excluding clip and support from FM due to the internal pressure.
b) displacements from the HX excluding clip and support from FM due to the acceleration of 42.43 g normal to the centreline of the HX.

9.1.1 FM HX Pressure deformation excluding clip and support

This analysis has been applied on the FE-Model, see fig. 7.
For the boundaries a clamp restrain on the whole surface where the two pipes are connected on the HX FM is used. See fig.8.
Load case:
The internal pressure has been set on a pressure level of 160 bar (equal to 16 MPa).
Results:
The maximum deformation is 0.0173 mm. See fig. 11 and 12.

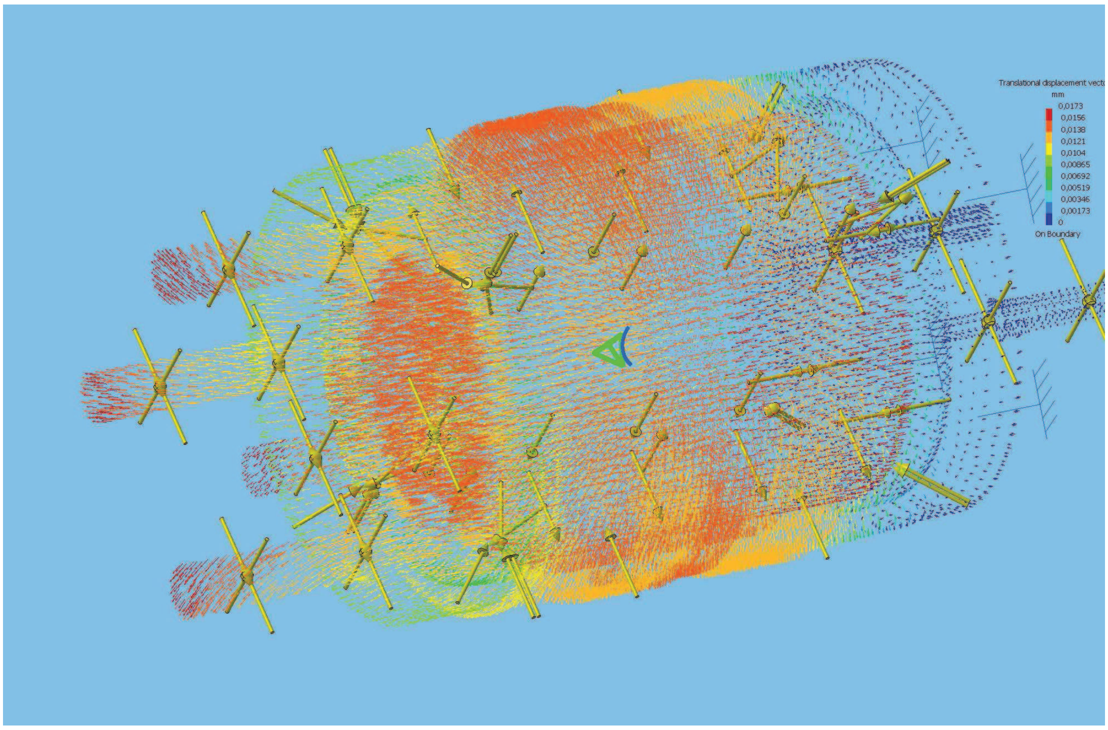


Figure 11. Deformation of HX (excl. clip and brackets) for internal pressure of 160 bar.

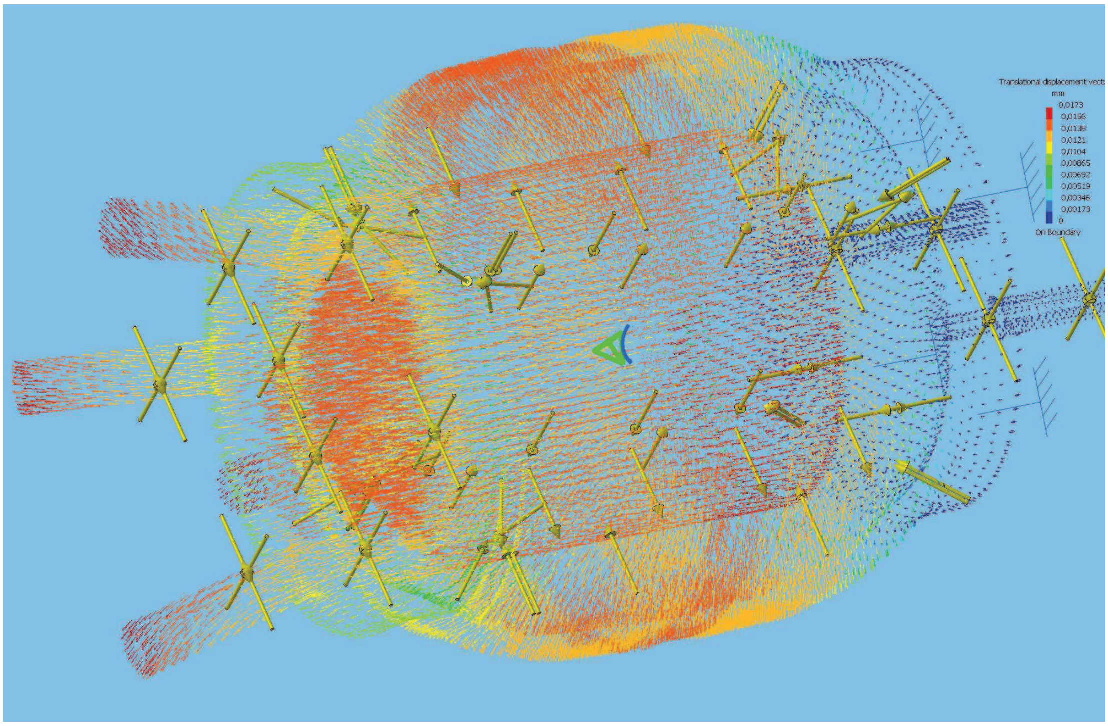


Figure 12. Deformation of HX (excl. clip and brackets) for internal pressure of 160 bar (deformed figure).

9.1.2 FM HX Acceleration deformation excluding clip and support

This analysis has been applied to the FE-model, see fig. 7.

For the boundaries a clamp restrain on the whole surface where the two pipes are connected on the HX FM is used. See fig.9.

Load case:

Normal to the centreline of the HX FM and normal to the base plate an acceleration level of 42.43 g has been applied.

Results:

The maximum deformation is 0.003 mm. See fig. 13.

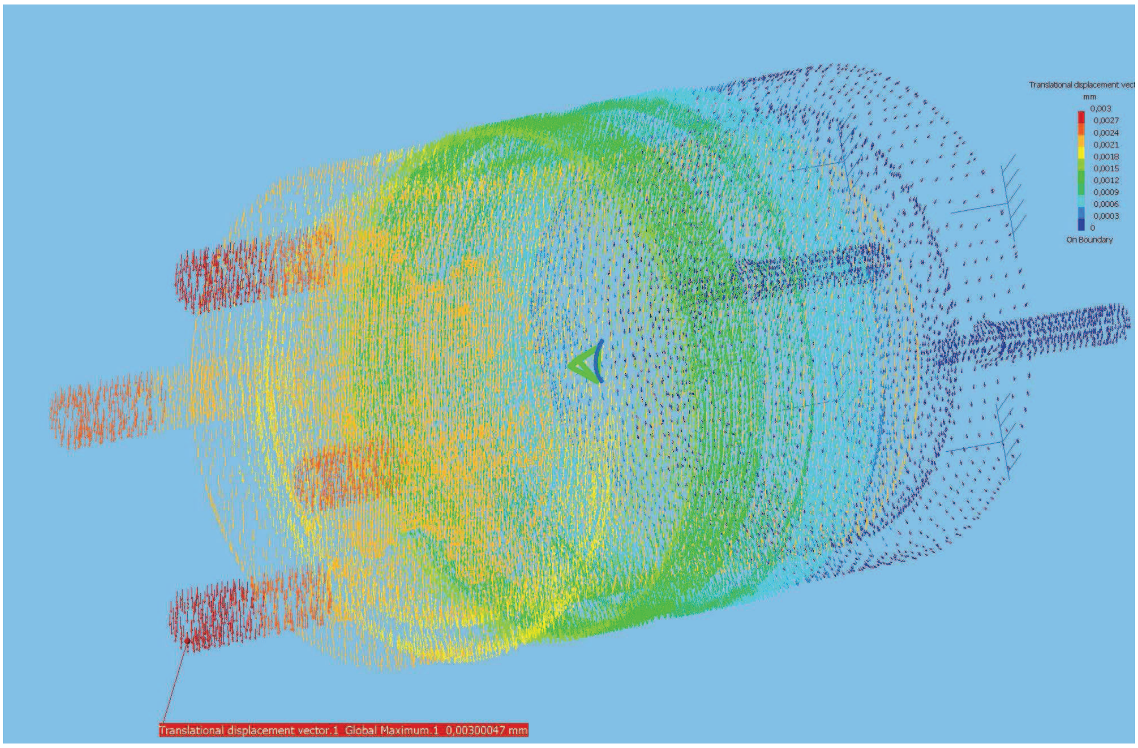


Figure 13. Deformation of HX (excl. clip and brackets) for acceleration of 42.43 g normal to base plate.

9.2 Heat eXchanger Flight Model stress analyses

Next stress concentrations of the Heat Exchanger FM (HX FM) have been analysed:

a) stress concentrations from the HX excluding clip and support from FM due to the internal pressure
b) stress concentrations from the HX excluding clip and support from FM due to the acceleration of 42.43 g normal to the centreline of the HX FM
c) Combined stress concentrations in HX excluding clip and support due pressure and acceleration
d) Thermal stress calculations including clip and support
e) Combined pressure and thermal stress loads excluding clip and support
f) Structural analyses of the HX clip

9.2.1 FM HX Pressure induced stress excluding clip and support

This analysis has been applied to the FE-model, see fig. 7. For the boundaries a clamp restrain on the whole surface where the two pipes are connected on the HX FM is used. See fig.9.

Load case:

An internal pressure on the container (including all tubes) and the centre part of the HX (heat exchanger assy) has been applied.

Results:

The maximum Von Mises nodal stress is 229 MPa. See fig. 16 and 17. This maximum occurs in the R2.35 area (see Appendix E)

The maximum Principal Stress is 254 MPa. See fig. 18.

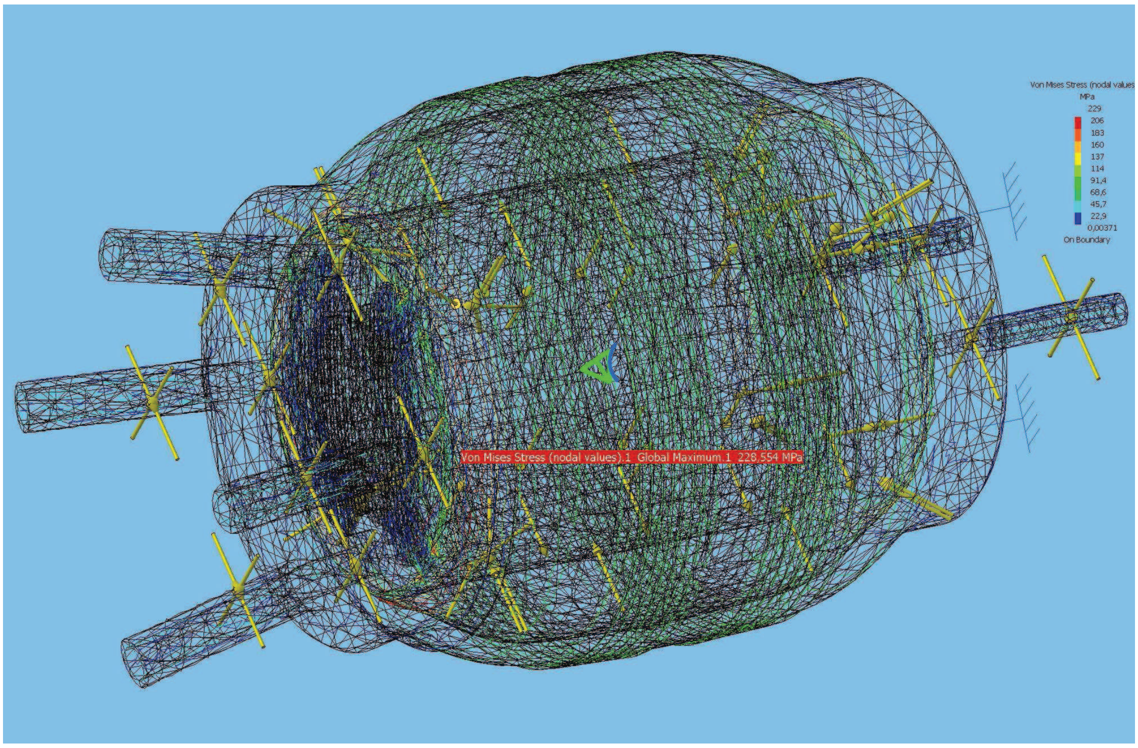


Figure 16. Maximum Von Mises Stress (nodal) is 228.5 MPa (container + heat exchanger).

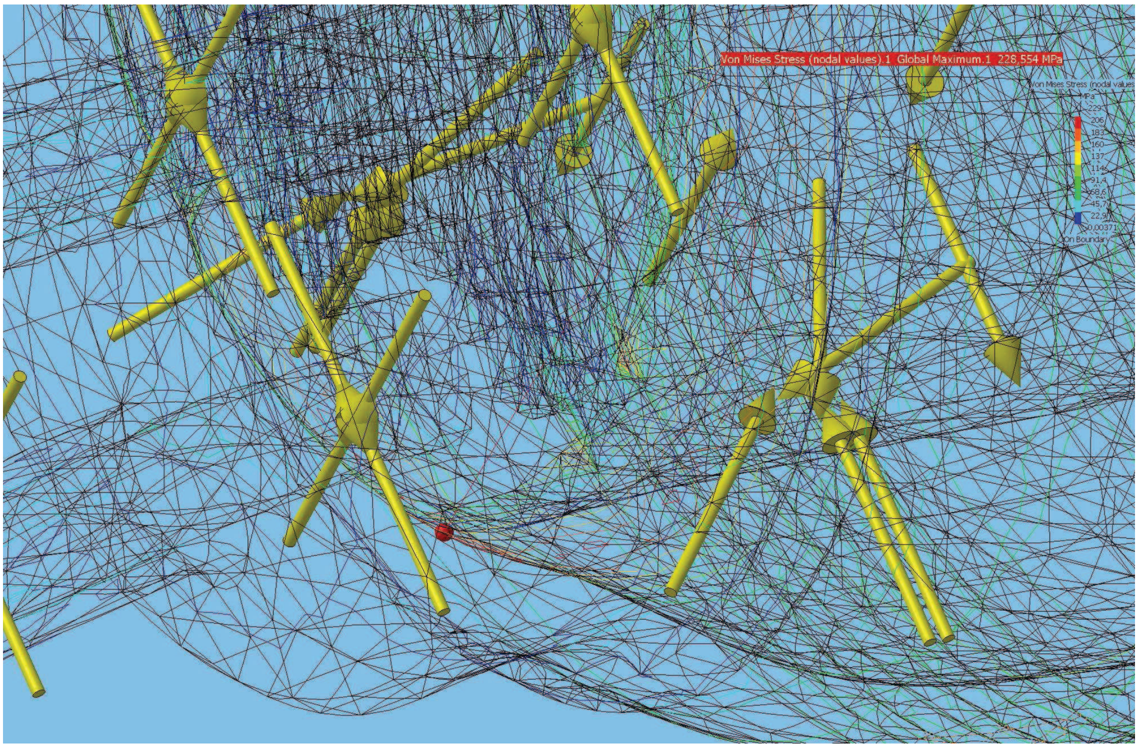


Figure 17. Maximum Von Mises Stress (nodal) is 228.5 MPa (Maximum in R2.35 area).

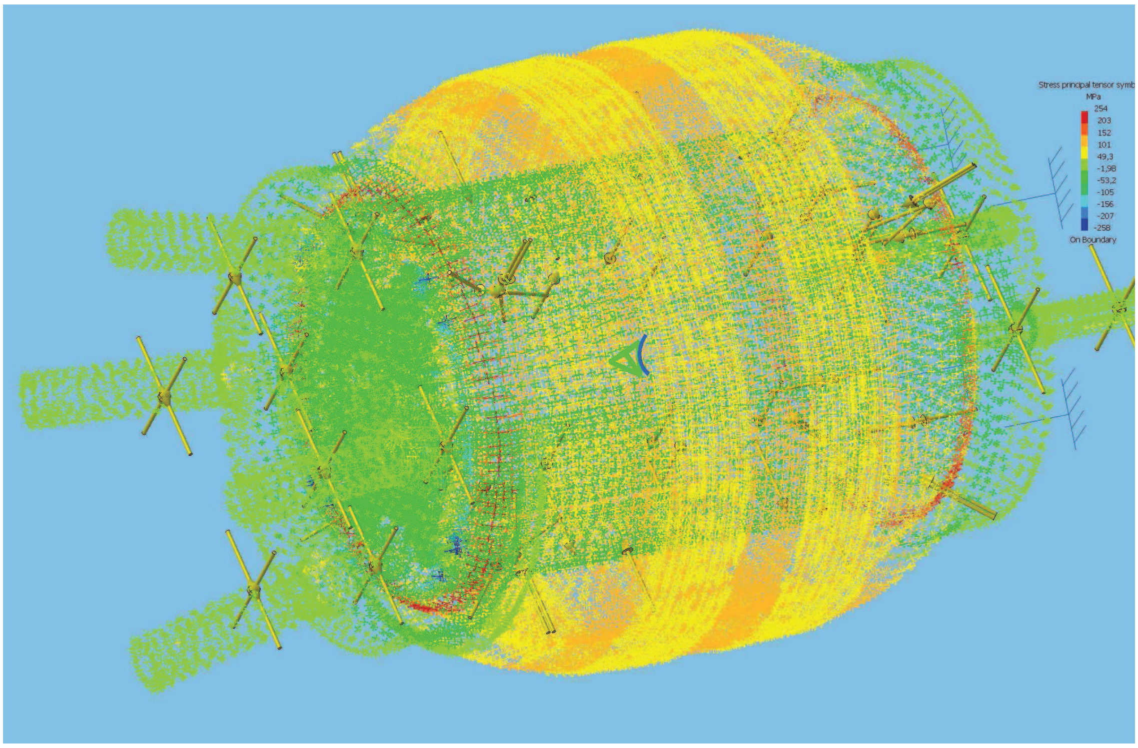


Figure 18. Maximum Principal Stress is 254 MPa (Maximum in R2.35 area).

Summary analysis results;

- Maximum Von Misses (nodal) stress: 229 MPa;

  Factor of Safety on Ultimate load: 876 / 229 = 3.82, MoS = 0.53

  Factor of Safety on Yield strength: 421 / 229 = 1.59, MoS = 0.23

- Maximum Principal Stress: 255 MPa;

  Factor of Safety on Ultimate load: 876 / 255 = 3.43, MoS = 0.37

  Factor of Safety on Yield strength: 421 / 255 = 1.65, MoS = 0.10

The highest stress is in the edge of the HX container as shown in Appendix E.

N.B. In principle the contact pressure of the clips will lower the stresses in the R2.35 area.

9.2.2 FM HX Acceleration induced stress excluding clip and support

This analysis has been applied to the FE-model, see fig. 7.

For the boundaries a clamp restrain on the whole surface where the two pipes are connected on the HX FM is used. See fig.9.

<u>Load case:</u>

Normal to the centreline of the HX FM and normal to the base plate an acceleration level of 42.43 g has been applied.

<u>Results:</u>

The maximum Von Mises nodal stress is 7 MPa. See fig. 19, and 20. This maximum occurs in the R2.35 area.

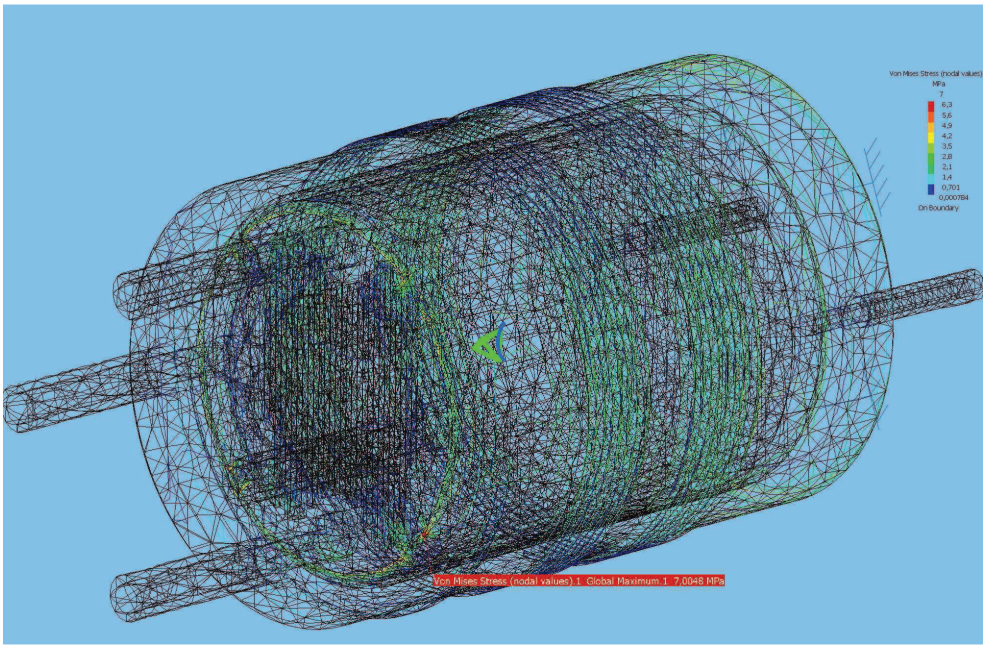


Figure 19. Maximum Von Mises nodal Stress due to acceleration of 42.43 g (container + heat exchanger).

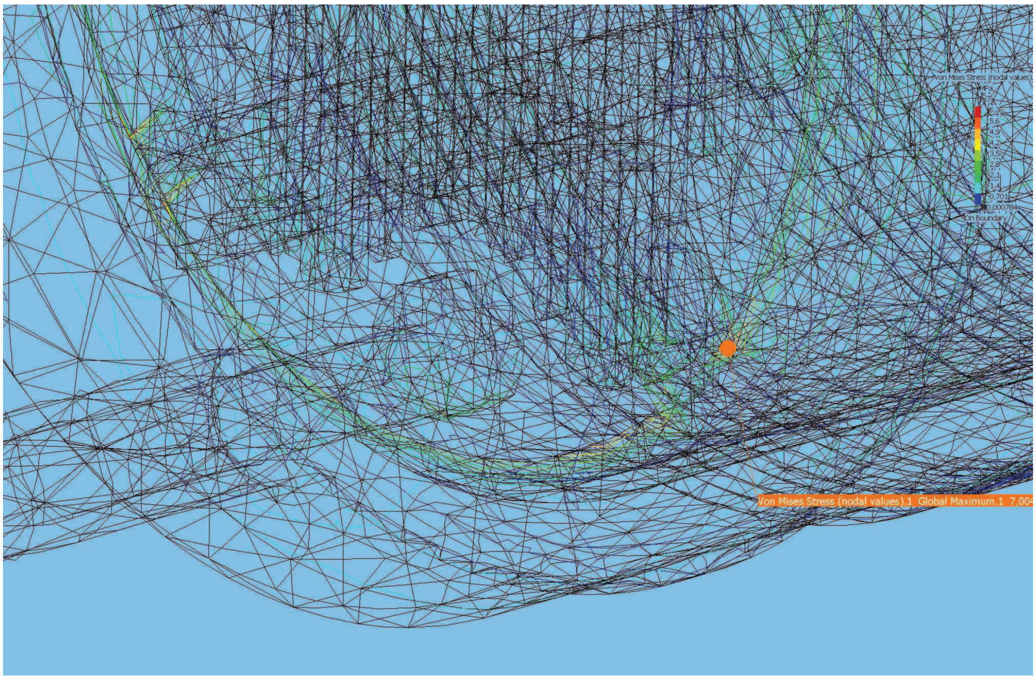


Figure 20. Maximum Von Mises nodal Stress due to acceleration of 42.43 g (detail).

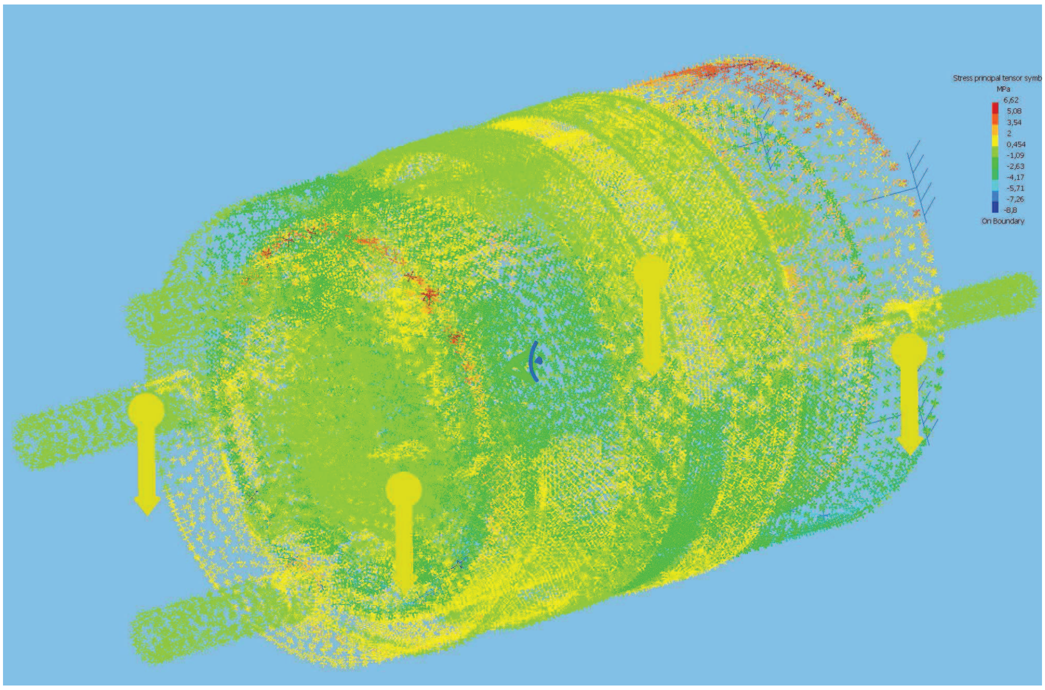


Figure 21. Maximum Principal Stress 6.62 MPa due to acceleration of 42.43 g normal to base plate.

Results:

The maximum Principal Stress is 7 MPa. See fig. 21. This maximum occurs in the R2.35 area.

9.2.3 FM HX stress by combined loads of internal pressure and acceleration

These analysis has been applied to the FE-model, see fig. 7.

For the boundaries a clamp restrain on the whole surface where the two pipes are connected on the HX FM is used. See fig.9.

Load case:

Two load cases are combined together; (See figure 22)

a) Load case: an internal pressure on the container (including all tubes) and the centre part of the HX (heat exchanger assembly) has been applied.

b) Load case: normal to the centreline of the HX FM and normal to the base plate a acceleration level of 42.43 g has been applied.

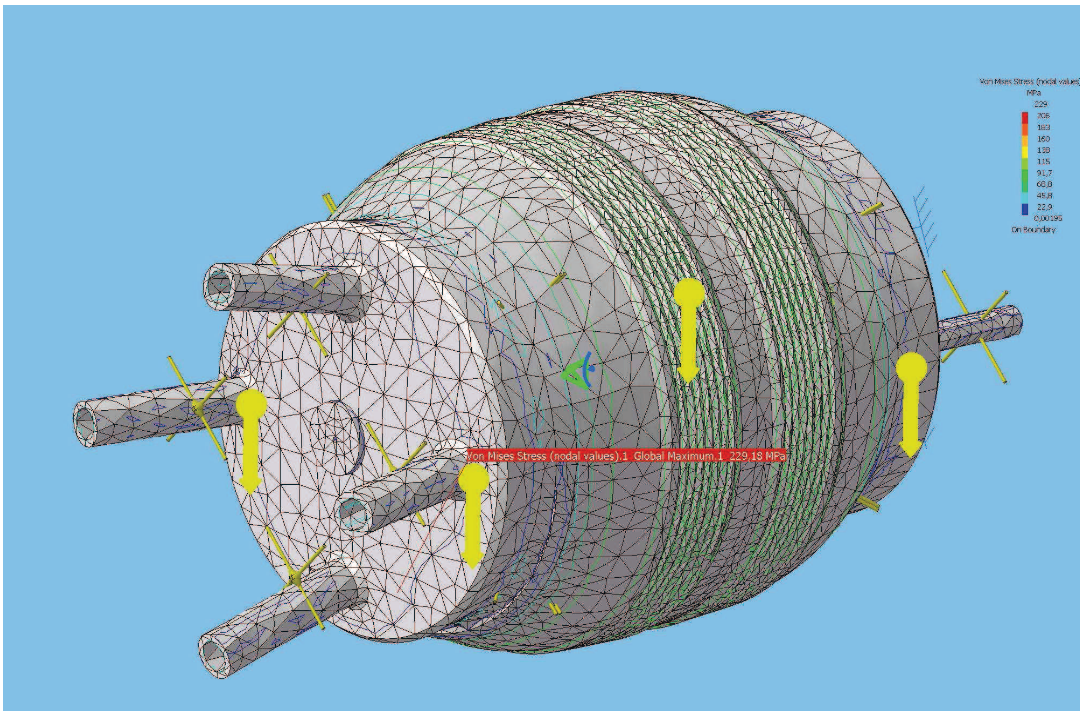


Figure 22. Combined load case (internal pressure 160 bar, acceleration 42.43 g normal to centre line HX and base plate (Von Mises nodal stress also presented).

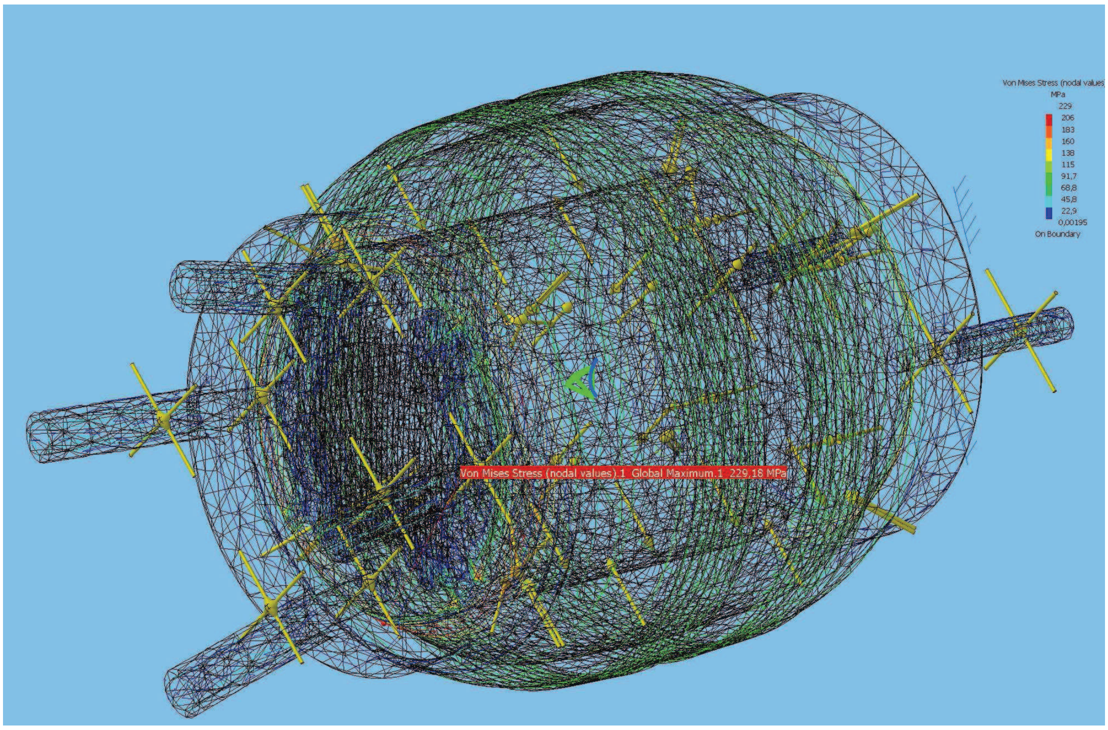


Figure 23. Von Mises nodal stress for combined load case (internal pressure 160 bar, acceleration 42.43 g normal to centre line HX and base plate.

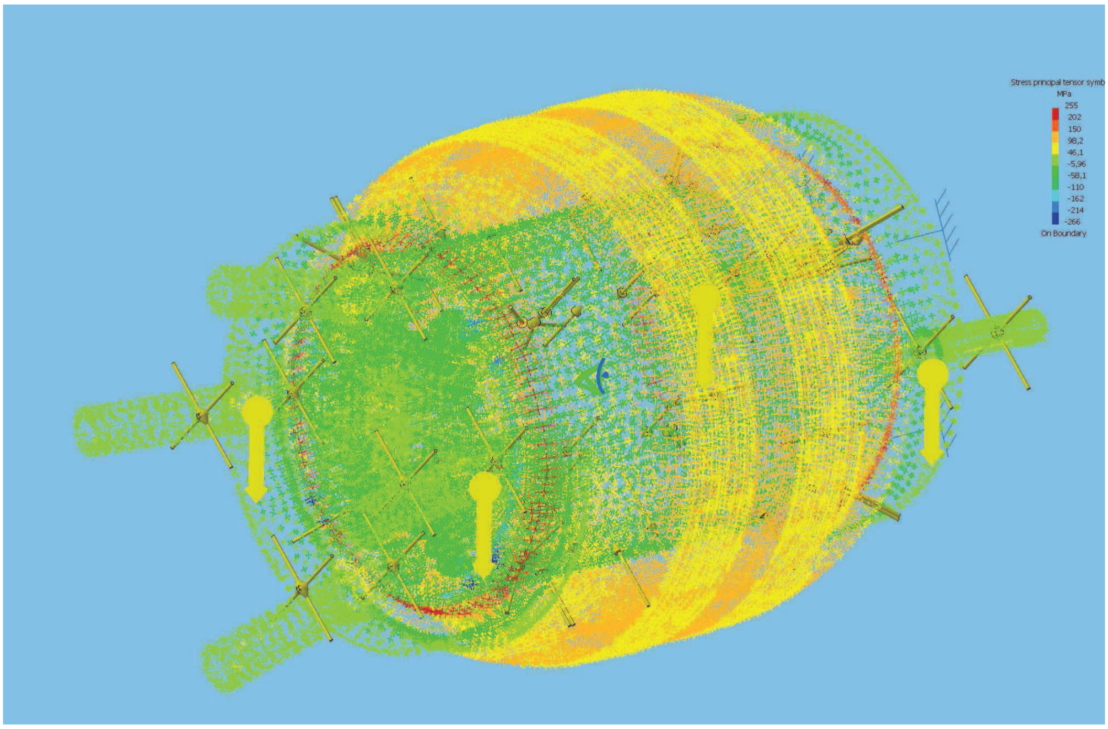


Figure 24. Principal stress for combined load case (internal pressure 160 bar, acceleration 42.43 g normal to centre line HX and base plate.

In the combined case when the direction of the acceleration is at the worst case the Von Mises nodal stress due to the internal pressure (160 bar) and the Von Mises nodal stress due to the acceleration of 42,43 g have to be summated.

This gives the following stresses and margins of safety:

- the total Von Mises nodal stress can be 229 + 7 = 236 MPa.
- the total Principal Stress can be 254 + 7 = 261 MPa.

In that case the Factor of Safety and Margin of Safety will be:
- Maximum Von Misses (nodal) stress: 236 MPa;
  - Factor of Safety on Ultimate load: 876 / 236 = 3.71, MoS = 0.48
  - Factor of Safety on Yield strength: 421 / 236 = 1.78, MoS = 0.19
- Maximum Principal Stress: 255 MPa;
  - Factor of Safety on Ultimate load: 876 / 262 = 3.04, MoS = 0.34
  - Factor of Safety on Yield strength: 421 / 262 = 1.39, MoS = 0.07

The highest stress location is again at the same location as indicated in Appendix E.

N.B. In principle the contact pressure of the clips will lower the stresses in the R2.35 area.

9.3 Thermal stress analysis

The temperature distribution in the heat exchanger used for the determination of the thermal stresses was presented in the "AMS TTCS Safety Approach" document. In this section a summary of the thermal calculation is given.

The maximum temperatures and the distribution are calculated at heater failure with SINDA.

The model of the heat exchanger built in Thermal Desktop is seen in Figure 9-1 Figure 9-2. The heater failure mode is defined as the case where both start-up heaters (A and B) are switched on resulting in a total power input of 100 [Watt]. Due to structural limitations, the heat exchanger is equipped with thermostats having a set point of 80 °C. The moment of TS switching is the worst case temperature distribution.

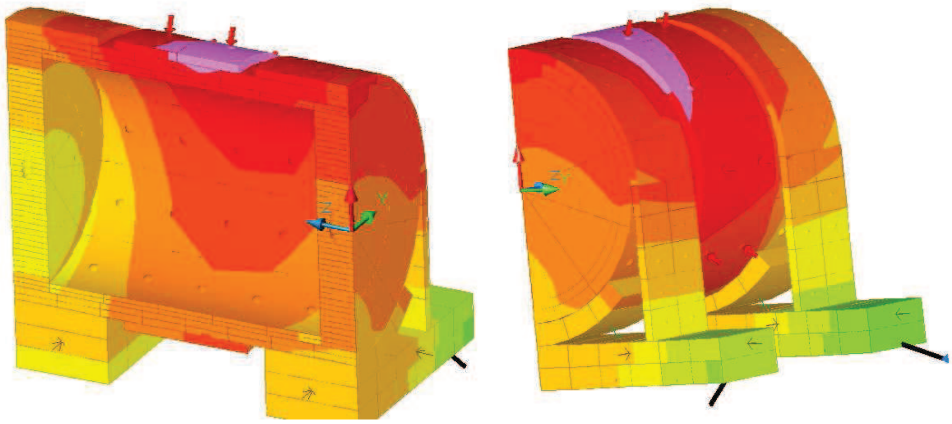


Figure 9-1: Front and backside view of the heat exchanger model (Without insert)

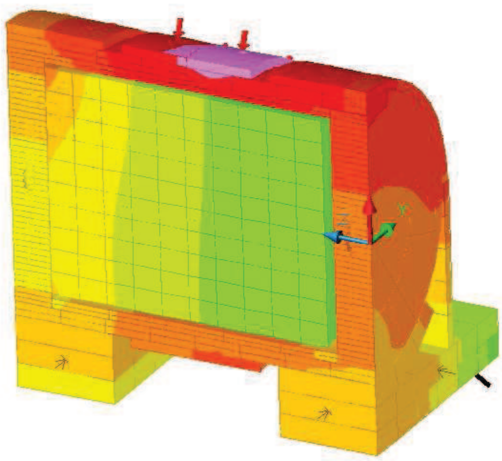


Figure 9-2: Front view of the heat exchanger model (With insert)

This temperature distribution was calculated with SINDA and is used as input of the Thermal Mechanical Stress Analyses and is shown in Figure 9-3.

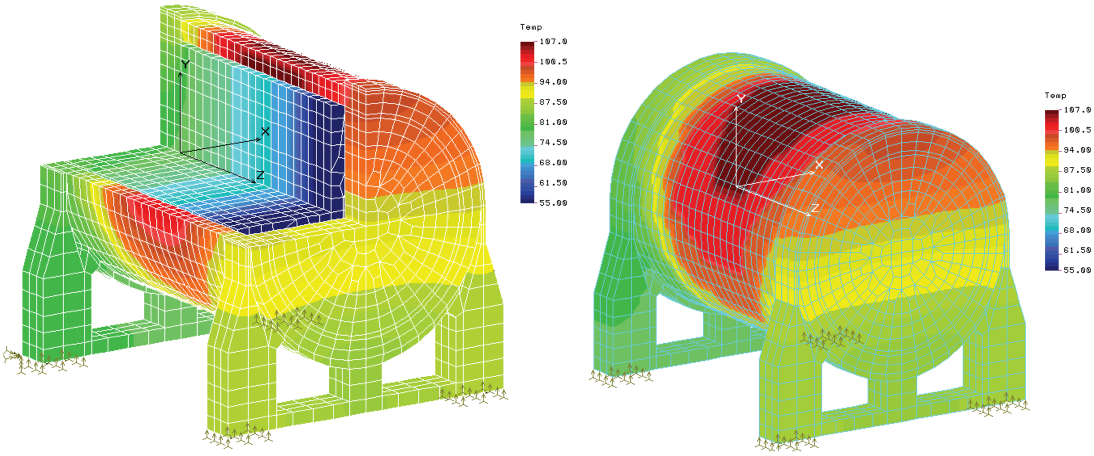


Figure 9-3: Temperature distribution in the heat exchanger due to heater failure

9.3.1 Thermal stress analysis Finite Element Model (FE-Model)

The used FE-model is a simplified version of the designed FM. Only the details of the FM which are of importance for the stress levels are simulated in the FE-model. The resulting Von Mises Stress induced by the worst case temperature distribution is seen in Figure 9-4.

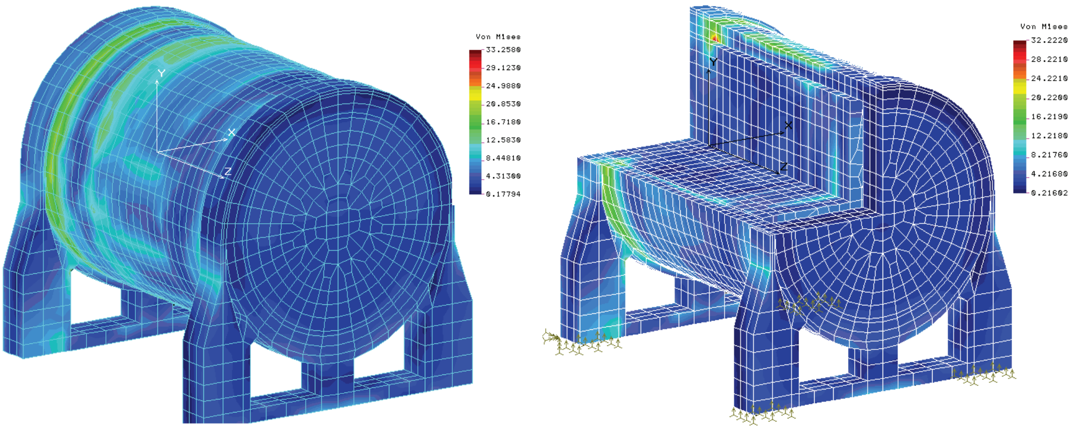


Figure 9-4: Resulting Von Mises Stress In the Heat Exchanger (Thermal Load Case, heater Control Failure)

The maximum occurring Von Mises stresses are found on the upper half of the heat exchanger as seen in red in Figure 9-4.

The absolute maximum stresses are summarized in below table and pictures.

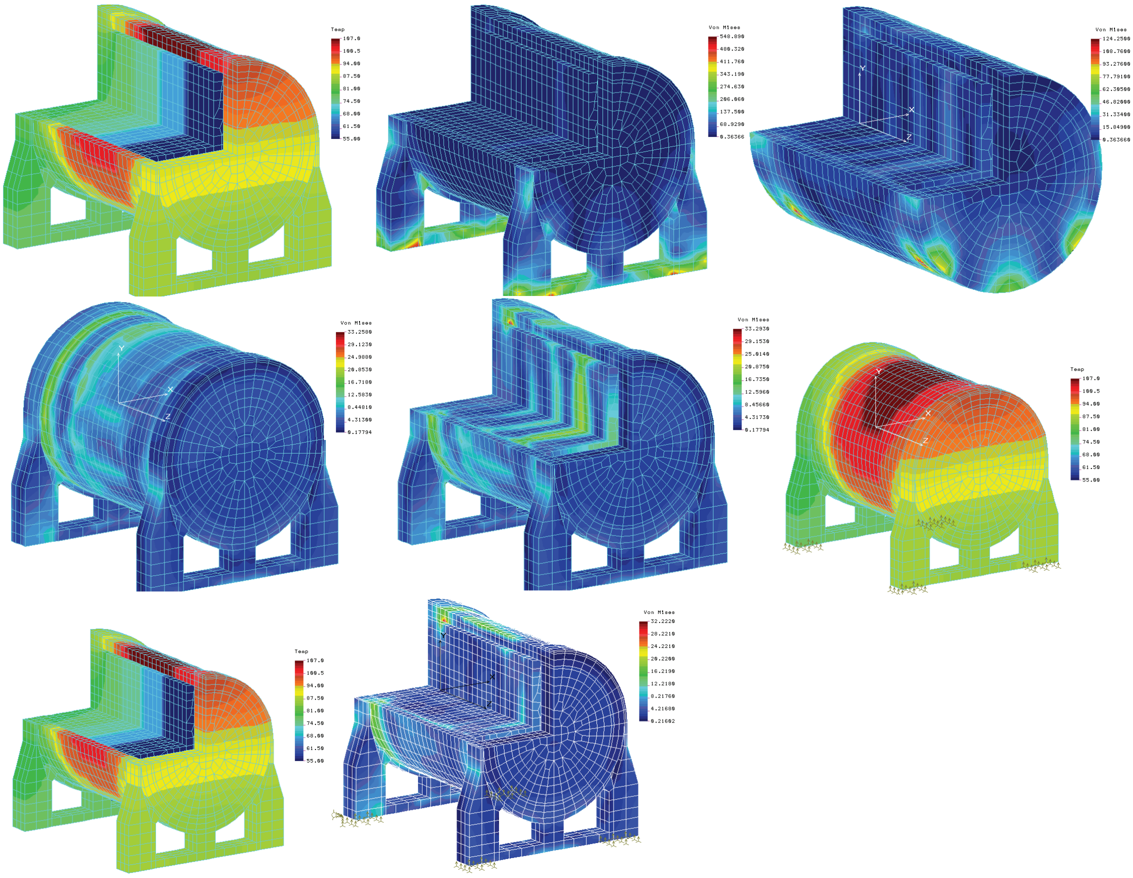


Figure 9-5: Resulting Von Mises Stress In the Heat Exchanger (Thermal Load Case, heater Control Failure)

Basic Stress Component	Max [MPa]	Shear Stress	Max [MPa]	Von Mises Stress	Max [MPa]
σ_x	20.87	τ_x	8.76	σ_{vm}	25.18
σ_y	23.07	τ_y	3.99		
σ_z	23.77	τ_z	4.08		

Principal Stress Component	Max [MPa]	Von Mises Stress	Max [MPa]
σ_1	24.35	σ_{vm}	32.22
σ_2	20.49		
σ_3	06.05		

Table 9-1: Maximum thermal stresses

9.4 MoS Summary

The Margins of safety for the HX structural analyses are summarised in below table.

	Acceleration Load Case	MDP Load Case 160 Bar	Thermal Load Case
Max Von Misses Stress [MPa]	7	229	32.2
Max Principle Stress [MPa]	7	255	24.3
Yield FoS_y [-]	1.5	1.5	1.5
Ultimate FoS_u [-]	2.5	2.5	2.5
Individual Load Cases			
Yield MoS_y Von Misses Stress	39	0.23	7.7
Ultimate MoS_y Von Misses Stress	49	0.53	9.9
Yield MoS_y Principle Stress	39	0.10	10.5
Ultimate MoS_y Principle Stress	49	0.37	13.4
Combined Load Cases (Acceleration + MDP)			
Yield MoS_y Von Misses Stress	0.19		
Ultimate MoS_y Von Misses Stress	0.48		
Yield MoS_y Principle Stress	0.07		
Ultimate MoS_y Principle Stress	0.34		
Combined Load Cases (MDP + Thermal)			
Yield MoS_y Von Misses Stress		0.07	
Ultimate MoS_y Von Misses Stress		0.34	
Yield MoS_y Principle Stress		0.005	
Ultimate MoS_y Principle Stress		0.25	

Table 9-2: Summary of margins of safety

FoS: Factor of Safety
MoS: Margin of Safety

10 Analyses for HX clip, support and bolts

To analyse the support and screw Margins of Safety the HX including all other parts (clip, support, Thermal Switches, Heat Wires and fasteners) have been loaded with an acceleration load of 42.43 g:

1) in the direction of the centreline of the HX,
2) in the direction perpendicular to 1) and perpendicular to the base plate and
3) in the direction perpendicular to 1) and 2)

10.1 HX Clip Analysis

The Clip analysis is given in Appendix C. The acceleration loads on the clip are the same as for the bolts analyses and can be found in Appendix F.
The worst case is shown in below table

Load case	Tension in section B-B [MPa]	Max [MPa]	Ultimate MoS	Yield MoS
Vertical acceleration normal to base plate	48	48	5.57	4.03

Table 10-1: Highest load case for the HX Clip

Additional stress is added to this tension by small expansion of the HX container at MDP as shown in section 9.1.1. The deformation of the HX on the location of the clip I/F is estimated on only 0.008 mm.

10.2 Bolts analyses

The acceleration load calculations for the bolts analyses are found in Appendix F. The calculated loads are used in the AMS standard bolts analysis method in Mathcad sheets. These Mathcad analyses include the bolt torque and load analyses and the fail-safe bolts analyses. The highest loaded fastener (per type) determines the minimum MoS.

The input excel files are found in Appendix D.

The MoS for the bolts are summarised in below table:

			Bolt load case		Fail safe case		Pre-load (nom)	Pre-load (min)	Pre-load (max)
Bolt-connection	**Load case description**	**Bolt**	**MoS**	**Failure mo**	**MoS**	**Failure mode**	**(lbf*in)**	**(lbf*in)**	**(lbf*in)**
HX to baseplate	Tensile load 424,3 m/s^2 in vertical direction normal to base plate	NAS1351N3-16	0.15	Total tension yield	0.38	Total thread shear ultimate	39	35.9	42.2
HX to baseplate	424,3 m/s^2 in horizontal direction	NAS1351N3-16	0.156	Total tension yield	0.38	Total thread shear ultimate	39	35.9	42.2
HX clip to HX support	Tensile load 424,3 m/s^2 in vertical direction normal to base plate	MS24694C52	0.035	Total tension yield	0.05	Joint separation	9.5	9	10.6
HX clip to HX support	424,3 m/s^2 in horizontal direction	MS24694C52	0.04	Total tension yield	1.22	Joint separation	9.5	9	10.6

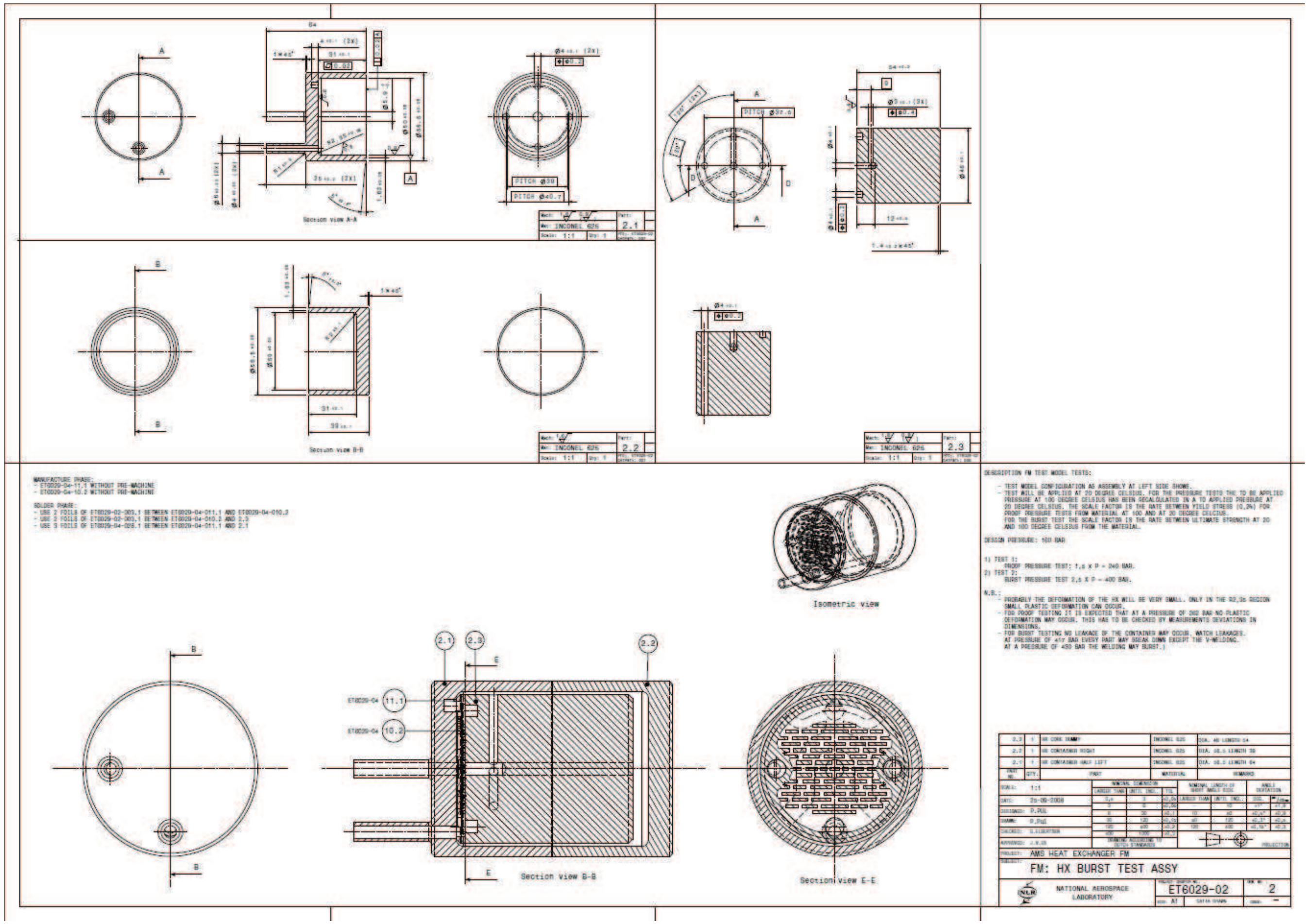
11 Conclusions

The structural analyses show all positive margins of safety for all worst cases analysed. The case with the smallest margin of safety is the combined pressure and thermal load case. The highest stress is found in an edge of the inner wall of the container. This area will be constrained by an additional clip not modelled in the current more worst case analyses. This additional clip will increase the margin.

The HX clip shows large margins of safety.
All bolts analyses show positive margins of safety.

To verify the structural integrity of the design an HX burst test sample was build and successfully tested.

12 Appendix A: TTCS HX Burst Test Sample



13 Appendix B: Inconel 625 Certificate

38

Deliver to: (if different)

MERREM & LA PORTE
HI-TECH MATERIALS
VEILINGWEG 2
ZALTBOMMEL
THE NETHERLANDS
NL-5301 KM

Customer: 130702

MERREM & LA PORTE
VEILINGWEG 2
POSTBUS 50
ZALTBOMMEL
THE NETHERLANDS
5300 CC

MAHER

CERTIFICATE OF CONFORMITY
No: 228407 Rev 1

Order Details		**Requirements**	**Certification**
Reference	K93543	A625 RND 63.500MM DIA ANN MCD GRADE 1 SUPPLY 1 CUT PIECE X 1000MM LONG 1	31B/MILL/SPEC
Part Number			
Quantity	1-OFF		
Diameter (MM)	063.50		
Weight (KGS)			

Cast Number	312694	**Incoming Certificate**	44109	**Melt Practice**	VIM/ESR	**Forge Reduction**	>=2:1/>=3:1
Country of Origin	GERMANY	**Test Report**		**Specification**	See comments below.		

Chemical analysis

Ag.	**Al.**	**B .**	**Bi.**	**C .**	**Co.**	**Cr.**	**Cu.**	**Fe.**	**Mg.**	**Mn.**	**Mo.**
	0.20			0.03	0.11	22.32		3.53		0.04	9.14
Ni.	**P .**	**Pb.**	**S .**	**Si.**	**Ti.**	**V .**	**W .**	**N .**	**Nb.**	**Ta.**	
60.65	0.004		0.001	0.06	0.31				3.48	<0.01	
Others											

Mechanical Properties

Test	**Units**		**Batch**	**Test Piece**
0.2% Proof Stres:	N/mm2		479	
Tensile Strength	N/mm2		913	
Elongation	4D		53	
Elongation	A5		51	
Redn of Area			60	
Hardness	HRC		30-31	
Charpies	J	-60C	148-150-148	
Lateral Expansion				
Heat Treatment			1030 DEG C 0.5HRS WQ	
Other test details			UST SATISFACTORY TO Q500 REV 4 FREE FROM MERCURY CONTAMINATION GRAIN SIZE 10-9.5 SURFACE ROUGHNESS Ra: 0.57uM TO ASTM B446 UNS N06625 BS3076 NA21 1989, AMS5666	
Comments			MANUFACTURERS REPORT ATTACHED 1-OFF 63.50MM DIA X 1000MM LONG TO WERKSTOFF 2.4856 Specification: ALLOY 625. BS3076NA21. AMS 5666E. NACE MR0175-2003. ASTM B446-00 UNS N06625 GR 1.	

Date: 21 AUG 06

MC-228407-1

MAR-CERTP1 Rev3

MERREM & LA PORTE B.V.
Our ref.: K93543 NLR
Your ref.: IO 26195
A1

For Maher Ltd

Robert Goddard
Quality Engineer

The material hereby certified complies with the order requirements referenced above and has been controlled in accordance with our EN ISO 9001:2000 and AS9100/A registration 0862013 with LROA

Page 1 of 1

14 Appendix C: Structural analysis of HX clip

PR6029: Heat Exchanger Analysis

Subject: Analysis of Clip

Date: 25-sep-06
By: G. Elbertsen, NLR-AVET revised by J. van Es for screw fixation
File: Analysis of clip V4_1.xls

In this document next items are analysed:
A) analysis clip:
B) bearing load on clip and bracket
C) Function of the internal pressure of the Heat eXchanger a)on the strength of the clip and b) the fixation screws from the clip on the bracket.

General data:

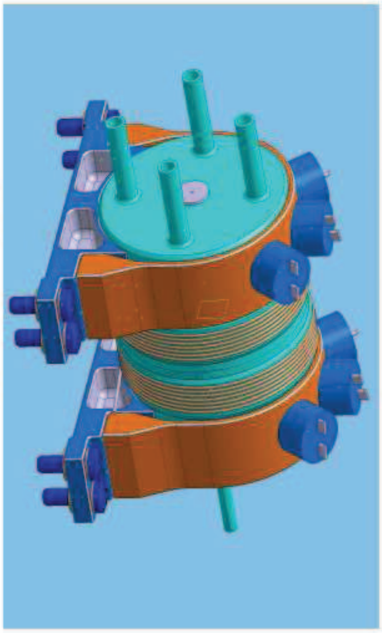


Fig. 1: Assembly Heat eXchanger

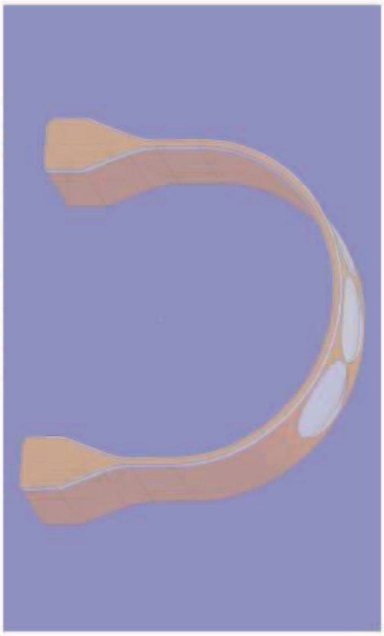


Fig. 2: Detail clip (incl. 3 pockets for thermo switches)

The strength of the clip, bracket and its fixation screws will be analysed in this file.

Material:

Clip	INCONEL 625
Bracket	INCONEL 625
Screws	CRES 316 (or INCONEL 718 if available)

1

A) analysis clip:

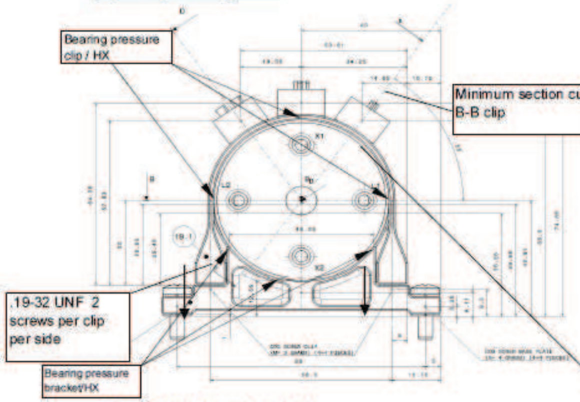


Fig. 3: Front View Assy HX.

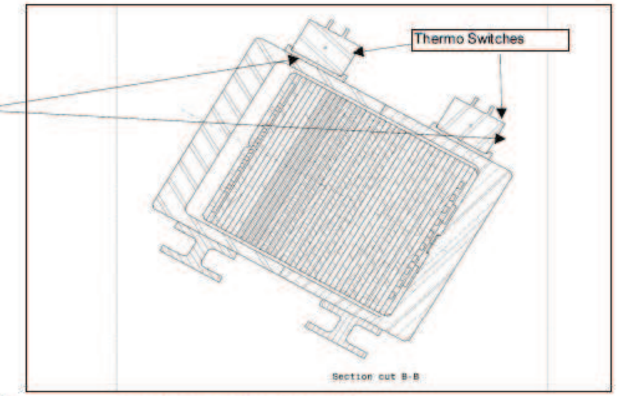


Fig. 4: Section cut BB from fig.3

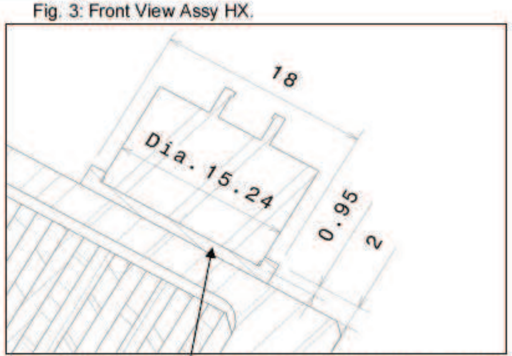


Fig. 5: Detail from section cut B-B over thermo switch connection pocket

Minimum section over clip beside the thermo switch: (fig.3 and 5)

width =	22	mm
thickness =	2	mm
section area =	44	mm2

Dimensions minimum section over thermo switches: (fig.5)

As minimum section over clip beside thermo switch minus cut off area for the cylindrical face fixation of the thermo swith, with a depth of 0.95 mm and a diameter of 15,24 mm

Minimum section area = =44-0,95*15,24 = 29.52 mm2

Material clip: INCONEL 625, cold-rolled annealed sheet

Material screw: CRES 316

Maximum work load in fixation screws of clip =	107.4 N.
Maximum tension in fixation screws of clip=	713.1 N.

Material screw: CRES 316

Maximum work load in fixation screws of clip =	107.4 N.
Maximum tension in fixation screws of clip=	3127.5 N.

Ref.: HX Acceleration loads on fixation V4.xls'

2

Mechanical propertes at 100 C from INCONEL 625, cold rolled annealed sheet): screws: CRES 316

Data from MIL-HDBK-5J. Wst.nr 2.4856

Ultimate strength:	794 MPa
Yield strength (0.2%):	364 MPa
Modulus of Elasticity:	191088.03 MPa
Mean linear expansion:	7.10E-06 mm/mm.K

FoS	for	Max.allowable stress
2.5	ultimate	318 MPa
1.5	yield	243 MPa

Analysis stress in clip due to tension in .19-32 UNF fasteners.

Ref. document: *HX Acceleration loads on fixation V3.xls*

Concluded was: Max. tension in one screw: 713.1 N

- In case of no friction between container of HX and clip:

in case of section area 22 x 2 mm:			44	mm2
Tension load by	2	screws .19-32 UNF:	1426.2	N
Tension in 18 x 2 section:			32	MPa
in case of section B - B area:			29.52	mm2
Tension load by	2	screws .19-32 UNF:	1426.2	N
Tension in section B - B:			48	MPa

stress Target: FoS on ultimate > 2.5 is OK
FoS on yield > 1.5 is OK

N.B. Bearing load will cause normal force and so friction.
Due to fibrations probably it is not allowed to take friction into accout.

Calculation of Factor of Safety of clips:

Factor of Safety based upon Ultimate strength:	16.43	=>	MoS=	5.57	(>0 is OK)
Factor of Safety based upon Yield stress:	7.54	=>	MoS=	4.03	(>0 is OK)

3

B) bearing load on clip and bracket screws: CRES 316

	Bearing load based on one screw load of:	713.1	N			
	Bearing load based upon 4 screws:	2852.4	N			
	Outer diameter HX:	56.5	mm			
	Width clip/bracket contact area:	21.0	mm	(Chamfer 0.5 (2X))		
	Width bracket contact area:	46.56	mm	(Chamfer 0.5 (2X))		
So,	Bearing pressure on clip:	2.40	MPa.	(compare this with	23.6	bar outside pressure)
	Bearing pressure on bracket:	2.92	MPa.	(compare this with	28.6	bar outside pressure)

This means that the internal pressure of the Heat eXchanger can play an important role in the stresses of the clip and that the bearing load of the clip/bracket can play an important role in the stresses of the Heat eXchanger

C) Function of the internal pressure of the Heat eXchanger a)on the strength of the clip and b) the fixation screws from the clip on the bracket.

The working pressure of the Heat eXchanger will be 35 bar, equal to: 3.5 MPa.

For the Flight Model FM:
The internal pressure of the Heat eXchanger will be constant at this level, so ideally 35 bar internal pressure should be present to torque the clip screws. The deformation of the HX at normal working pressure is so low that this is deemed unnecessary.

NB. The loads in the screws will become higher due to expanding from the container on Max. design pressure (16 Bar) become higher. also the stresses in the clips will slightly increase.
The local HX deformation at the clip is estimated on only 0.008 mm see section 9.1.1.

Function of the internal pressure of the Heat eXchanger on the strength of the container of the Heat eXchanger.

High stress concentrations occur in the edges fr 713 N, beside the clip a pressure from outside on the container wall of
Both clips and brackets are located at the outer side of the container in the neighbc 2.92 MPa acts on the container.
In case of a tension load per screw of
2.40 MPa acts on the container. Near the bracket a local pressure of
In a small area there is no clip or no bracket which is touching the container. There is no outside pressure on the container.
This means in this small area there is no advantage or a smaller advantange from this external pressure. This is why the advantage from outside pressure is not taken into account by the analysis of the HX.
also the stresses in the clips will

4

15 Appendix D: Bolts analyses input sheets

Input List for Bolt Templates

Project Name: AMS Heat Exchanger FM Primary Loop	Joint Description: HX support to baseplate connection			Contact Info: J. van Es (NLR)
Bolt Information				
Description	**Variable**	**Input**	**Unit**	**Reference**
Part Number	N/A	ET6029-04 part 31.2	N/A	NAS1351N3-10
Material	N/A	CRES 316	N/A	
Ultimate Tensile Allowable	Ftu_bolt	160000	psi	1.10E+09
Yield Tensile Allowable	Fty_bolt	120000	psi	8.27E+08
Temperature correction factor for ultimate (hot)	TSu_bolt	0.94	N/A	
Temperature correction factor for yield (hot)	TSy_bolt	0.94	N/A	
Modulus of elasticity	E_bolt	2.91E+07	psi	2.01E+11
Temperature correction factor for modulus (hot)	TE_bolt	0.94	N/A	
Thermal coeffecient (hot)	α_bolt_hot	9.10E-06	in/in/degF	
Thermal coeffecient (cold)	α_bolt_cold	7.80E-06	in/in/degF	
Nominal Diameter of Bolt	D	0.19	in	
Total Length of Bolt	L	1	in	
Threaded Length of Bolt	Lt	1	in	
Number of threads/inch	Nt	32	1/in	
Bolt head diameter across flats	dw	0.312	in	
Insert Information				
Part Number	N/A	ET 5998-06 part 10.6	N/A	Insert MS21209 F1-15
Material	N/A	A286	N/A	
Ultimate Tensile Allowable	Ftu_ins	150000	psi	
Temperature correction factor for ultimate (hot)	TS_ins	0.94	N/A	
Length of Insert	Lins	0.285	in	
Min. external diameter of insert	Fmin	0.236	in	
Depth of recess for insert	lr	0	in	
Washer Information				
Part Number	N/A	ET 6029-04 Part 31.4	N/A	NAS 620 10 LC
Material	N/A	CRES 316	N/A	
Modulus of elasticity	E_washer	2.60E+07	psi	
Temperature correction factor for modulus (hot)	TE_washer	1	N/A	in mm
Thickness of washer	tw	0.032	in	0.8128
Outer diameter of washer	Dw	0.354	in	8.9916
Inner diameter of washer	Dwi	0.195	in	4.953
Thermal washer information				
Part Number	N/A	Part ET 5998-06 15.8	N/A	
Material	N/A	Ti6A14V	N/A	
Modulus of elasticity	E_washer	1.69E+07	psi	
Temperature correction factor for modulus (hot)	TE_washer	1	N/A	in mm
Thickness of washer	tw	0.0512	in	1.30048
Outer diameter of washer	Dw	0.394	in	10.0076
Inner diameter of washer	Dwi	0.197	in	5.0038
Flange Information				
Part Number for flange 1	N/A	ET6029-04 part 19.2	N/A	
Material for flangle 1	N/A	Inconel 625	N/A	
Part Number for flange 2	N/A	ET 5998-06 part 10.1	N/A	
Material for flangle 2	N/A	AL 7475 T7351	N/A	in mm
Thickness of flange 1	tf1	0.2264	in	5.75056
Thickness of flange 2	tf2	0.5906	in	15.00124
Diameter of thru hole	D_hole	0.197	in	5.0038
Modulus of elasticity for flange 1	E_flange1	2.77E+07	psi	1.91E+11
Modulus of elasticity for flange 2	E_flange2	1.03E+07	psi	7.10E+10
Temperature correction factor for modulus flangle 1(hot)	Tf1E	1	N/A	
Temperature correction factor for modulus flangle 2(hot)	Tf2E	1	N/A	
Temperature correction factor for ultimate (hot)	Tf2s	0.91	N/A	
Shear Allowable	Fsu_f2	27000	psi	1.86E+08
Thermal coeffecient of flange 1(hot)	α_flange1_hot	7.10E-06	in/in/degF	
Thermal coeffecient of flange 1(cold)	α_flange1_cold	7.10E-06	in/in/degF	
Thermal coeffecient of flange 2(hot)	α_flange2_hot	1.22E-05	in/in/degF	
Thermal coeffecient of flange 2(cold)	α_flange2_cold	1.15E-05	in/in/degF	
Loads, Factor of Safety, Temperature, and Torque Information				
Loads Model	N/A	AMS HX Model	N/A	
Load Case	N/A	Acceleration loads	N/A	HX Accelaration loads on fixation.xls
Applied tensile load	P	59.85	lbf	266.2128
Applied shear load	V	0	lbf	0
Applied bending moment	M	0	in-lbf	
Ultimate factor of safety	SFu	2	N/A	
Yield factor of safety	SFy	1.5	N/A	1.25 ???
Joint seperation factor of safety	SFsep	1.2	N/A	
Fitting Factor	FF	1.15	N/A	
Assembly temperature	Temp_initial	22	C	
Maximum temperature	Temp_max	80	C	
Minimum temperature	Temp_min	-50	C	Nm
Maximum torque	Tmax	42.2	in-lbf	4.77
Minimum torque	Tmin	35.9	in-lbf	4.06
Torque coefficient	k	0.15	N/A	
Loading plane factor	n	0.5	N/A	
Preload uncertainty	Γ	0.25	N/A	
Applied tensile load (fail-safe)	P	74.995	lbf	333.57776
Applied shear load (fail-safe)	V	0	lbf	0

Input List for Bolt Templates

Project Name:	Joint Description:	Contact Info:
AMS Heat Exchanger FM Primary Loop	HX support to baseplate connection	J. van Es (NLR)

Bolt Information

Description	Variable	Input	Unit	Reference
Part Number	N/A	ET6029-04 part 31.2	N/A	NAS1351N3-10
Material	N/A	CRES 316	N/A	
Ultimate Tensile Allowable	Ftu_bolt	160000	psi	1.10E+09
Yield Tensile Allowable	Fty_bolt	120000	psi	8.27E+08
Temperature correction factor for ultimate (hot)	TSu_bolt	0.94	N/A	
Temperature correction factor for yield (hot)	TSy_bolt	0.94	N/A	
Modulus of elasticity	E_bolt	2.91E+07	psi	2.01E+11
Temperature correction factor for modulus (hot)	TE_bolt	0.94	N/A	
Thermal coeffecient (hot)	α_bolt_hot	9.10E-06	in/in/degF	
Thermal coeffecient (cold)	α_bolt_cold	7.80E-06	in/in/degF	
Nominal Diameter of Bolt	D	0.19	in	
Total Length of Bolt	L	1	in	
Threaded Length of Bolt	Lt	1	in	
Number of threads/inch	Nt	32	1/in	
Bolt head diameter across flats	dw	0.312	in	

Insert Information

Description	Variable	Input	Unit	Reference
Part Number	N/A	ET 5998-06 part 10.6	N/A	Insert MS21209 F1-15
Material	N/A	A286	N/A	
Ultimate Tensile Allowable	Ftu_ins	150000	psi	
Temperature correction factor for ultimate (hot)	TS_ins	0.94	N/A	
Length of Insert	Lins	0.285	in	
Min. external diameter of insert	Fmin	0.236	in	
Depth of recess for insert	lr	0	in	

Washer Information

Description	Variable	Input	Unit	Reference
Part Number	N/A	ET 6029-04 Part 31.4	N/A	NAS 620 10 LC
Material	N/A	CRES 316	N/A	
Modulus of elasticity	E_washer	2.60E+07	psi	
Temperature correction factor for modulus (hot)	TE_washer	1	N/A	in mm
Thickness of washer	tw	0.032	in	0.8128
Outer diameter of washer	Dw	0.354	in	8.9916
Inner diameter of washer	Dwi	0.195	in	4.953

Thermal washer information

Description	Variable	Input	Unit	Reference
Part Number	N/A	Part ET 5998-06 15.8	N/A	
Material	N/A	Ti6A14V	N/A	
Modulus of elasticity	E_washer	1.69E+07	psi	
Temperature correction factor for modulus (hot)	TE_washer	1	N/A	in mm
Thickness of washer	tw	0.0512	in	1.30048
Outer diameter of washer	Dw	0.394	in	10.0076
Inner diameter of washer	Dwi	0.197	in	5.0038

Flange Information

Description	Variable	Input	Unit	Reference
Part Number for flange 1	N/A	ET6029-04 part 19.2	N/A	
Material for flangle 1	N/A	Inconel 625	N/A	
Part Number for flange 2	N/A	ET 5998-06 part 10.1	N/A	
Material for flangle 2	N/A	AL 7475 T7351	N/A	in mm
Thickness of flange 1	tf1	0.2264	in	5.75056
Thickness of flange 2	tf2	0.5906	in	15.00124
Diameter of thru hole	D_hole	0.197	in	5.0038
Modulus of elasticity for flange 1	E_flange1	2.77E+07	psi	1.91E+11
Modulus of elasticity for flange 2	E_flange2	1.03E+07	psi	7.10E+10
Temperature correction factor for modulus flangle 1(hot)	Tf1E	1	N/A	
Temperature correction factor for modulus flangle 2(hot)	Tf2E	1	N/A	
Temperature correction factor for ultimate (hot)	Tf2s	0.91	N/A	
Shear Allowable	Fsu_f2	27000	psi	1.86E+08
Thermal coeffecient of flange 1(hot)	α_flange1_hot	7.10E-06	in/in/degF	
Thermal coeffecient of flange 1(cold)	α_flange1_cold	7.10E-06	in/in/degF	
Thermal coeffecient of flange 2(hot)	α_flange2_hot	1.22E-05	in/in/degF	
Thermal coeffecient of flange 2(cold)	α_flange2_cold	1.15E-05	in/in/degF	

Loads, Factor of Safety, Temperature, and Torque Information

Description	Variable	Input	Unit	Reference
Loads Model	N/A	AMS HX Model	N/A	
Load Case	N/A	Acceleration loads	N/A	HX Accelaration loads on fixation V6.xls
Applied tensile load	P	24.92	lbf	110.84416
Applied shear load	V	21.34	lbf	94.92032
Applied bending moment	M	0	in-lbf	
Ultimate factor of safety	SFu	2	N/A	
Yield factor of safety	SFy	1.5	N/A	1.25 ???
Joint seperation factor of safety	SFsep	1.2	N/A	
Fitting Factor	FF	1.15	N/A	
Assembly temperature	Temp_initial	22	C	
Maximum temperature	Temp_max	80	C	
Minimum temperature	Temp_min	-50	C	
Maximum torque	Tmax	42.2	in-lbf	
Minimum torque	Tmin	35.9	in-lbf	
Torque coefficient	k	0.15	N/A	
Loading plane factor	n	0.5	N/A	
Preload uncertainty	Γ	0.25	N/A	
Applied tensile load (fail-safe)	P	34.71	lbf	154.39008
Applied shear load (fail-safe)	V	21.34	lbf	94.92032

Input List for Bolt Templates

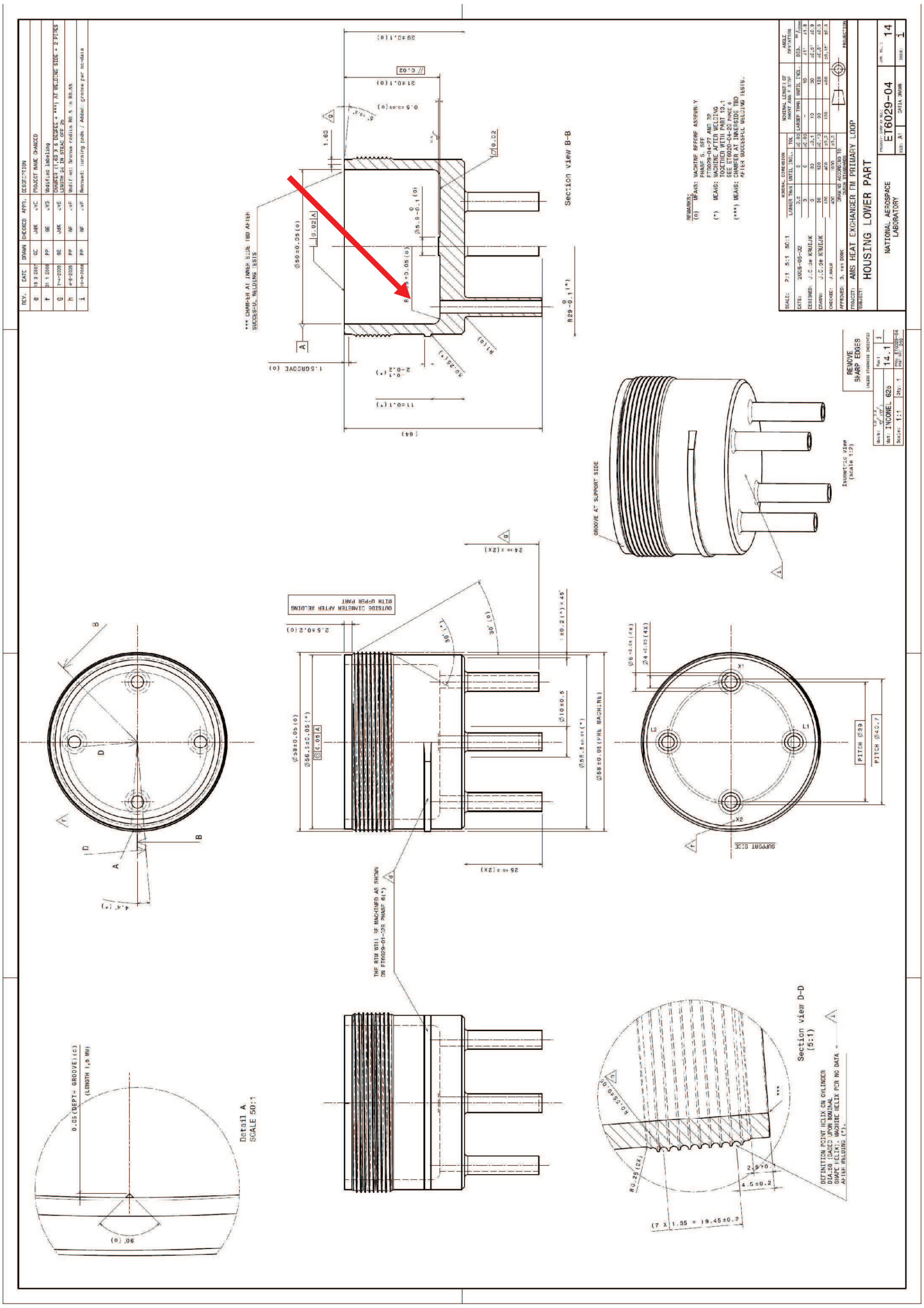
Project Name:	Joint Description:	Contact Info:
AMS Heat Exchanger FM Primary Loop	HX Clip to support connection (only tensile)	J. van Es (NLR)

Description	Variable	Input	Unit	Reference
Bolt Information				
Part Number	N/A	ET6029-04 part 31.3	N/A	Bolt countersunkhead MS 24694C52
Material	N/A	CRES 316	N/A	
Ultimate Tensile Allowable	Ftu_bolt	85000	psi	5.86E+08
Yield Tensile Allowable	Fty_bolt	30000	psi	2.07E+08
Temperature correction factor for ultimate (hot)	TSu_bolt	0.94	N/A	
Temperature correction factor for yield (hot)	TSy_bolt	0.94	N/A	
Modulus of elasticity	E_bolt	2.90E+07	psi	2.00E+11
Temperature correction factor for modulus (hot)	TE_bolt	0.94	N/A	
Thermal coeffecient (hot)	α_bolt_hot	9.10E-06	in/in/degF	
Thermal coeffecient (cold)	α_bolt_cold	7.80E-06	in/in/degF	
Nominal Diameter of Bolt	D	0.19	in	4.83
Total Length of Bolt	L	0.656	in	16.66
Threaded Length of Bolt	Lt	0.468	in	11.89
Number of threads/inch	Nt	32	1/in	
Bolt head diameter across flats	dw	0.327	in	abs min taken
Insert Information				
Part Number	N/A	ET6029-04 part 31.1	N/A	Insert MS21209 F1-20L
Material	N/A	A286	N/A	Corrosion resistant steel
Ultimate Tensile Allowable	Ftu_ins	150000	psi	
Temperature correction factor for ultimate (hot)	TS_ins	0.94	N/A	
Length of Insert	Lins	0.38	in	9.652
Min. external diameter of insert	Fmin	0.236	in	5.9944
Depth of recess for insert	lr	0	in	?
Washer Information				
Part Number	N/A		N/A	
Material	N/A		N/A	
Modulus of elasticity	E_washer		psi	
Temperature correction factor for modulus (hot)	TE_washer		N/A	**No washer**
Thickness of washer	tw		in	
Outer diameter of washer	Dw		in	
Inner diameter of washer	Dwi		in	
Tapped Hole Information				
Part Number of tapped flange	N/A		N/A	
Material	N/A		N/A	
Ultimate Tensile Allowable	Ftu_f2		psi	**No tapped hole but insert**
Shear Allowable	Fsu_f2		psi	
Temp. correction factor for flange with tapped hole (hot)	TS_f2		N/A	
Depth of bolt into tapped hole	Ltap		in	
Flange Information				
Part Number for flange 1	N/A	ET 6029-04 Part 19.2	N/A	ET 6029-04 TTCS HX Support
Material for flangle 1	N/A	Inconel 625	N/A	
Part Number for flange 2	N/A	ET 6029-04 Part 19.1	N/A	ET 6029-04 TTCS HX Clip
Material for flangle 2	N/A	Inconel 625	N/A	in mm
Thickness of flange 1	tf1	0.2756	in	7.00024
Thickness of flange 2	tf2	0.38	in	depth of insert
Diameter of thru hole	D_hole	0.988	in	25.0952
Modulus of elasticity for flange 1	E_flange1	2.77E+07	psi	1.91E+11
Modulus of elasticity for flange 2	E_flange2	2.77E+07	psi	1.91E+11
Temperature correction factor for modulus flangle 1(hot)	Tf1E	1	N/A	
Temperature correction factor for modulus flangle 2(hot)	Tf2E	1	N/A	
Temperature correction factor for ultimate (hot)	Tf2s	0.91	N/A	educated guess
Shear Allowable	Fsu_f2	115000	psi	7.93E+08
Thermal coeffecient of flange 1(hot)	α_flange1_hot	7.10E-06	in/in/degF	1.28E-05
Thermal coeffecient of flange 1(cold)	α_flange1_cold	7.00E-06	in/in/degF	1.26E-05
Thermal coeffecient of flange 2(hot)	α_flange2_hot	7.10E-06	in/in/degF	1.28E-05
Thermal coeffecient of flange 2(cold)	α_flange2_cold	7.00E-06	in/in/degF	1.26E-05
Loads, Factor of Safety, Temperature, and Torque Information				
Loads Model	N/A	AMS HX Model	N/A	tensile and shear
Load Case	N/A	Acceleration loads	N/A	in N
Applied tensile load	P	42.3	lbf	188.1504
Applied shear load	V	0	lbf	0
Applied bending moment	M	0	in-lbf	
Ultimate factor of safety	SFu	2	N/A	
Yield factor of safety	SFy	1.25	N/A	??
Joint seperation factor of safety	SFsep	1.2	N/A	
Fitting Factor	FF	1.15	N/A	
Assembly temperature	Temp_initial	71.6	C	
Maximum temperature	Temp_max	176	C	
Minimum temperature	Temp_min	-58	C	Analysis of clip V4.xls nominal 1951.4 Nmm
Maximum torque	Tmax	10.6	in-lbf	1197.60479
Minimum torque	Tmin	9	in-lbf	1016.834256
Torque coefficient	k	0.25	N/A	
Loading plane factor	n	0.15	N/A	
Preload uncertainty	Γ	0.5	N/A	
Applied tensile load (fail-safe)	P	51.8	lbf	230.4064
Applied shear load (fail-safe)	V	0	lbf	0

Input List for Bolt Templates

Description	Variable	Input	Unit	Reference
Project Name: AMS Heat Exchanger FM Primary Loop	**Joint Description:** HX Clip to support connection (only tensile)			**Contact Info:** J. van Es (NLR)
Bolt Information				
Description	**Variable**	**Input**	**Unit**	**Reference**
Part Number	N/A	ET6029-04 part 31.3	N/A	Bolt countersunkhead MS 24694C52
Material	N/A	CRES 316	N/A	
Ultimate Tensile Allowable	Ftu_bolt	85000	psi	5.86E+08
Yield Tensile Allowable	Fty_bolt	30000	psi	2.07E+08
Temperature correction factor for ultimate (hot)	TSu_bolt	0.94	N/A	
Temperature correction factor for yield (hot)	TSy_bolt	0.94	N/A	
Modulus of elasticity	E_bolt	2.90E+07	psi	2.00E+11
Temperature correction factor for modulus (hot)	TE_bolt	0.94	N/A	
Thermal coeffecient (hot)	α_bolt_hot	9.10E-06	in/in/degF	
Thermal coeffecient (cold)	α_bolt_cold	7.80E-06	in/in/degF	
Nominal Diameter of Bolt	D	0.19	in	4.83
Total Length of Bolt	L	0.656	in	16.66
Threaded Length of Bolt	Lt	0.468	in	11.89
Number of threads/inch	Nt	32	1/in	
Bolt head diameter across flats	dw	0.327	in	abs min taken
Insert Information				
Part Number	N/A	ET6029-04 part 31.1	N/A	Insert MS21209 F1-20L
Material	N/A	A286	N/A	Corrosion resistant steel
Ultimate Tensile Allowable	Ftu_ins	150000	psi	
Temperature correction factor for ultimate (hot)	TS_ins	0.94	N/A	
Length of Insert	Lins	0.38	in	9.652
Min. external diameter of insert	Fmin	0.236	in	5.9944
Depth of recess for insert	lr	0	in	?
Washer Information				
Part Number	N/A		N/A	
Material	N/A		N/A	
Modulus of elasticity	E_washer		psi	
Temperature correction factor for modulus (hot)	TE_washer		N/A	**No washer**
Thickness of washer	tw		in	
Outer diameter of washer	Dw		in	
Inner diameter of washer	Dwi		in	
Tapped Hole Information				
Part Number of tapped flange	N/A		N/A	
Material	N/A		N/A	
Ultimate Tensile Allowable	Ftu_f2		psi	**No tapped hole but insert**
Shear Allowable	Fsu_f2		psi	
Temp. correction factor for flange with tapped hole (hot)	TS_f2		N/A	
Depth of bolt into tapped hole	Ltap		in	
Flange Information				
Part Number for flange 1	N/A	ET 6029-04 Part 19.2	N/A	ET 6029-04 TTCS HX Support
Material for flangle 1	N/A	Inconel 625	N/A	
Part Number for flange 2	N/A	ET 6029-04 Part 19.1	N/A	ET 6029-04 TTCS HX Clip
Material for flangle 2	N/A	Inconel 625	N/A	in mm
Thickness of flange 1	tf1	0.2756	in	7.00024
Thickness of flange 2	tf2	0.38	in	depth of insert
Diameter of thru hole	D_hole	0.988	in	25.0952
Modulus of elasticity for flange 1	E_flange1	2.77E+07	psi	1.91E+11
Modulus of elasticity for flange 2	E_flange2	2.77E+07	psi	1.91E+11
Temperature correction factor for modulus flangle 1(hot)	Tf1E	1	N/A	
Temperature correction factor for modulus flangle 2(hot)	Tf2E	1	N/A	
Temperature correction factor for ultimate (hot)	Tf2s	0.91	N/A	educated guess
Shear Allowable	Fsu_f2	115000	psi	7.93E+08
Thermal coeffecient of flange 1(hot)	α_flange1_hot	7.10E-06	in/in/degF	1.28E-05
Thermal coeffecient of flange 1(cold)	α_flange1_cold	7.00E-06	in/in/degF	1.26E-05
Thermal coeffecient of flange 2(hot)	α_flange2_hot	7.10E-06	in/in/degF	1.28E-05
Thermal coeffecient of flange 2(cold)	α_flange2_cold	7.00E-06	in/in/degF	1.26E-05
Loads, Factor of Safety, Temperature, and Torque Information				
Loads Model	N/A	AMS HX Model	N/A	tensile and shear
Load Case	N/A	Acceleration loads	N/A	in N
Applied tensile load	P	17.67	lbf	78.59616
Applied shear load	V	18.17	lbf	80.82016
Applied bending moment	M	0	in-lbf	
Ultimate factor of safety	SFu	2	N/A	
Yield factor of safety	SFy	1.25	N/A	??
Joint seperation factor of safety	SFsep	1.2	N/A	
Fitting Factor	FF	1.15	N/A	
Assembly temperature	Temp_initial	71.6	C	
Maximum temperature	Temp_max	176	C	
Minimum temperature	Temp_min	-58	C	Analysis of clip V4.xls nominal 1951.4 Nmm
Maximum torque	Tmax	10.6	in-lbf	1197.60479
Minimum torque	Tmin	9	in-lbf	1016.834256
Torque coefficient	k	0.25	N/A	
Loading plane factor	n	0.15	N/A	
Preload uncertainty	Γ	0.5	N/A	
Applied tensile load (fail-safe)	P	24.61	lbf	109.46528
Applied shear load (fail-safe)	V	18.008	lbf	80.099584

16 Appendix E: Drawing with high stress location indication



17 Appendix F: Hand calculations acceleration loads

AMS HEAT EXCHANGER QM-MODEL.

Subject: HX Acceleration loads on fixation
File: HX Acceleration loads on fixation V6.xls
By: G. Elbertsen - NLR-AVET
Date: 10 th of April 2008

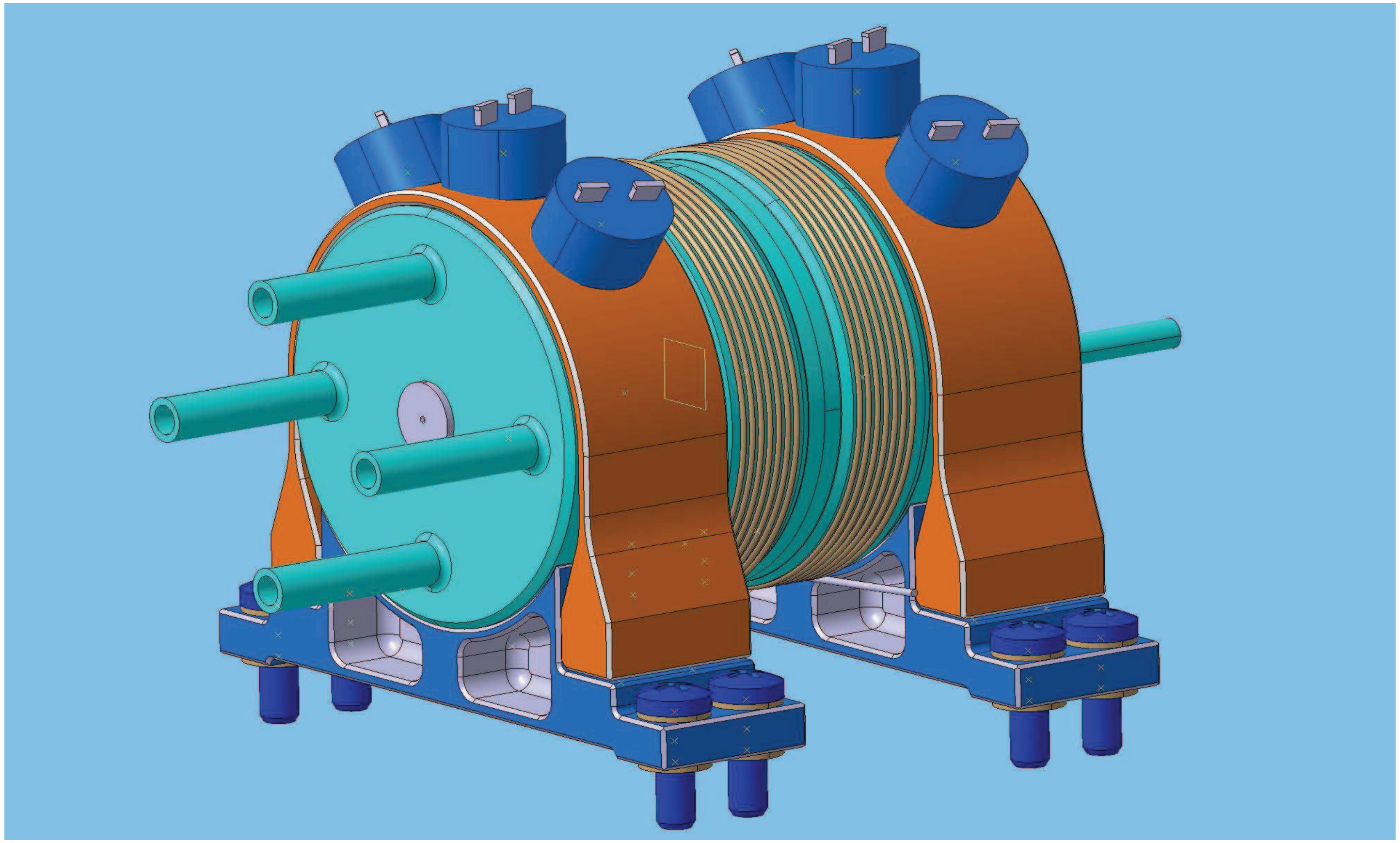
V6 modification: Determination max **work** loads on screws for bolt calculations J.v.Es (NLR)

ACCELERATION LOADS;

Defined acceleration loads:

g x =	40 g	=	400	m/s2
g y =	10 g	=	100	m/s2
g z =	10 g	=	100	m/s2
g 3d =	42.43 g	=	424.3	m/s2

N.B. The orientation of the HX in the space vehicle is unknown, so the acceleration loads are situated on HX in the most bad way, this is to find out the most critical screw load cases.



CO_2- mass:

Volume of CO_2 L+G;
52.426 [cm3]
(Anylized in CATIA)
Density CO_2- liquid:
1032 [kg/m3

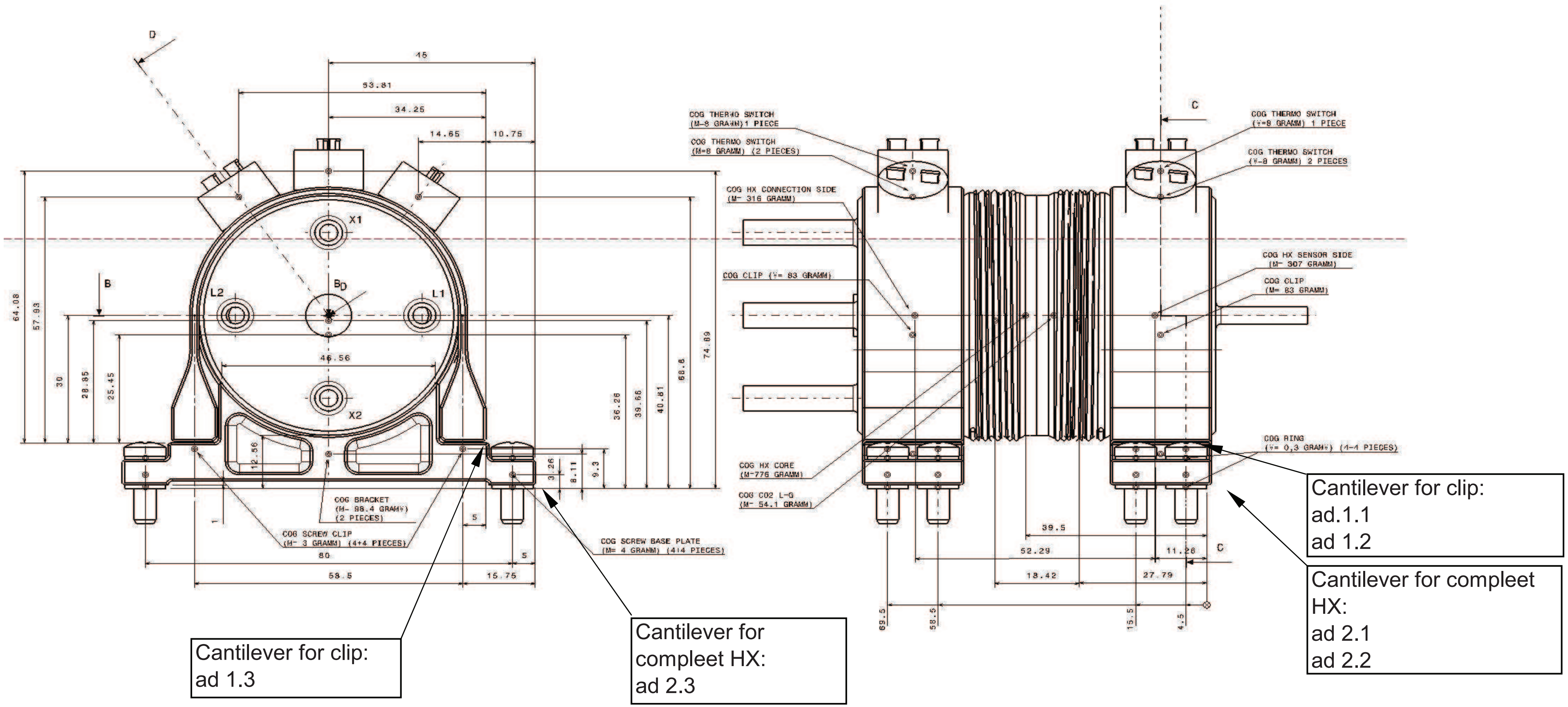
Mass CO_2-liquid:
0.0541 kg

Mass of empty HX;
1.7357 kg

Total Mass HX:
1.7898 kg.

DIMENSIONS OF HX WITH Centre of Gravity, mass points;

DIMENSIONS WILL CHANGE A LITTLE DUE TO DESIGN CHANGE.



Analysis of the screws;

2 screw connections: Case 1) fixation from clip on bracket
Case2) fixation from bracket on base

NB. There is a small asymmetry in the mass distribution due to inside of the HX: this deviation has been neglected (until know).

ad. 1) Fixation from clip on bracket:

3 load cases:

1.1) acceleration of 424,3 m/s2 acts in vertical direction upward, normal to base plate.
1.2) acceleration of 424,3 m/s2 acts in horiozontal direction in the Right view to the right.
1.3) acceleration of 424,3 m/s2 acts in horiozontal direction in the Front view to the right.

ad. 2) Fixation from bracket on base:

2.1) acceleration of 424,3 m/s2 acts in vertical direction upward, normal to base plate.
2.2) acceleration of 424,3 m/s2 acts in horiozontal direction in the Right view to the right.
2.3) acceleration of 424,3 m/s2 acts in horiozontal direction in the Front view to the right.

Case 1: **(acceleration of 424,3 m/s2 acts in vertical direction upward, normal to base plate)** Screw for Clip

Remark *: Rotation point at right side of right bracket in Right view.

ad. 1.1:

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	63.55	8956.77
HX 2 pipes	0.3218	136.53	11.26	1537.31
HX core	0.5943	252.14	46.21	11651.40
clip left	0.0867	36.78	64.50	2372.55
clip right	0.0867	36.78	10.50	386.23
3 ThermoSwi	0.0240	10.18	64.50	656.76
3 ThermoSwi	0.0240	10.18	10.50	106.91
CO_2- liquid	0.0541	22.95	33.80	775.80
Total acceleration load:		646.49 [N]		
		Total moment:		26444 [Nmm]

The influence of the washers is not taken into account in all calculations below. The mass of a washer is very low.

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	69.5	2	139
left mid	58.5	1.6834532	98.482014
right mid	15.5	0.5299145	8.2136752
right	4.5	0.1294964	0.5827338
		Total bolt moment:	246.27842 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 107.37 N (tension for screws)
Resultante (force) = 646.49 N (tension for screws)
Maximum tension load on M4 screw: **188.18** N. (Max. work load + Resultante / number of screws)
COG of resultant (force): 40.90 mm from rotation pt

Case 1: **acceleration of 424,3 m/s2 acts in horiozontal direction in the Right view to the right.**

Screw for Clip

Remark *: Rotation point at right side of the right bracket in Right view.

ad. 1.2:

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	30.00	4228.22
HX 2 pipes	0.3218	136.53	30.00	4095.85
HX core	0.5943	252.14	28.85	7274.24
clip left	0.0867	36.78	25.45	936.15
clip right	0.0867	36.78	25.45	936.15
4 ThermoSwi	0.0320	13.58	57.93	786.48
2 ThermoSwi	0.0160	6.79	64.08	434.99
CO_2- liquid	0.0541	22.95	28.85	662.18
Total acceleration load:		646.49 [N]		
		Total moment:	19354 [Nmm]	

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	69.5	2	139
left mid	58.5	1.6834532	98.482014
right mid	15.5	0.5299145	8.2136752
right	4.5	0.1294964	0.5827338
		Total bolt moment:	246.27842 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 78.59 N (tension for screws)

Resultante (force) = 646.49 N (shear for screws)

Shear load on M4 screws: 80.81 N. (shear load / number of screws)

COG of resultant (force): 29.94 mm from rotation pt

Case 1: **acceleration of 424,3 m/s2 acts in horiozontal direction in the Front view to the right.**

Screw for Clip

ad. 1.3: Remark *: Rotation point at right side of the brackets in Front view.

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	30.00	4228.22
HX 2 pipes	0.3218	136.53	30.00	4095.85
HX core	0.5943	252.14	28.85	7274.24
clip left	0.0867	36.78	25.45	936.15
clip right	0.0867	36.78	25.45	936.15
2 ThermoSwi	0.0160	6.79	53.31	361.88
2 ThermoSwi	0.0160	6.79	33.75	229.10
2 ThermoSwi	0.0160	6.79	14.15	96.05
CO_2- liquid	0.0541	22.95	28.85	662.18
Total load due to acceleration:		646.49 [N]		
		Total moment:	18820 [Nmm]	

Equilibrium for screws:

Position (4 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	63	4	252
right	4.5	0.2857143	1.2857143
		Total bolt moment:	253.28571 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 74.3 N (tension for screws)

Resultante (force) = 646.49 N (shear for screws)

Shear load on M4 screws: 80.81 N. (shear load / number of screws)

COG of resultant (force): 29.11 mm from rotation pt

CONCLUSION MAXIMUM SCREW LOAD ON SCREWS FOR CLIP

NB. All screws are in service.

Summary screw load as calculated before;

ad. 1.1:	Maximum tension load on M4 screw:	188.18	N
	Shear load on M4 screws:	0.00	N.
	Torque screw:	TBD	N.mm
ad. 1.2:	Maximum tension load on M4 screw:	78.59	N
	Shear load on M4 screws:	80.81	N.
	Torque screw:	TBD	N.mm
ad. 1.3:	Maximum tension load on M4 screw:	74.30	N
	Shear load on M4 screws:	80.81	N.
	Torque screw:	TBD	N.mm

Conclusion for the determination of the Factor of Safety for the screws which fixate the HX by the clips:

The screw load factors of safety have to be calculated for situation ad. 1.1 and ad. 1.2. Ad. 1.3 is less critical as ad. 1.2.
The screw load factors of safety depends also of;

1) the torque on the screws and friction coëfficients. Torque pre loads the screws
2) the temperature differences in case of different thermal coëfficients of the materials

Case 2: **(acceleration of 424,3 m/s2 acts in vertical direction upward, normal to base plate)**

Screws for compleet HX

ad. 2.1:

Remark *: Rotation point at right side of right bracket for Right view.

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	63.55	8956.77
HX 2 pipes	0.3218	136.53	11.26	8676.37
HX core	0.5943	252.14	46.21	16023.51
clip left	0.0867	36.78	64.50	2372.55
clip right	0.0867	36.78	10.50	386.23
3 ThermoSwitch L 3pc	0.0240	10.18	64.50	656.76
3 ThermoSwitch R 3p	0.0240	10.18	10.50	106.91
CO_2- liquid	0.0541	22.95	33.80	775.80
Bracket Left	0.1222	51.85	64.50	3344.01
Bracket Right	0.1222	51.85	10.50	544.37
4 Screws L clip M4x10	0.0108	4.58	64.50	295.54
4 Screws R clip M4x12	0.0108	4.58	10.50	48.11
Total load due to acceleration:		759.35 [N]		
		Total moment:		42187 [Nmm]

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	69.5	2	139
left mid	58.5	1.6834532	98.482014
right mid	15.5	0.5299145	8.2136752
right	4.5	0.1294964	0.5827338
		Total bolt moment:	246.27842 [Fb.mm]

So, screw loads are:

left	171.3	N
left mid	144.2	N
right mid	45.4	N
right	11.1	N

Conclusion:

Maximum work load on M4 screw: 171.30 N (tension for screws)

Resultante (force) = 759.35 N (tension for screws)

Maximum tension load on M4 screw: **266.22** N. (Max. work load + Resultante / number of screws)

In this case no shear occurs.

COG of resultant (force): 55.56 mm from rotation pt

Case 2: **acceleration of 424,3 m/s2 acts in horiozontal direction in the Right view to the right.**

Screws for compleet HX

ad. 2.2:

Remark *: Rotation point at right side of right bracket for Right view.

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	40.81	5751.78
HX 2 pipes	0.3218	136.53	40.81	5571.71
HX core	0.5943	252.14	39.66	9999.88
clip left	0.0867	36.78	36.26	1333.78
clip right	0.0867	36.78	36.26	1333.78
4 ThermoSwitch L 4pc	0.0320	13.58	68.80	934.06
2 ThermoSwitch R 2pc	0.0160	6.79	74.89	508.37
CO_2- liquid	0.0541	22.95	40.81	936.70
Bracket Left	0.1222	51.85	8.11	420.46
Bracket Right	0.1222	51.85	8.11	420.46
4 Screws L clip M4x10	0.0108	4.58	9.30	42.61
4 Screws R clip M4x12	0.0108	4.58	9.30	42.61
Total load due to acceleration:		759.35 [N]		
			Total moment:	27296 [Nmm]

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	69.5	2	139
left mid	58.5	1.6834532	98.482014
right mid	15.5	0.5299145	8.2136752
right	4.5	0.1294964	0.5827338
		Total bolt moment:	246.27842 [Fb.mm]

Conclusion:

Maximum work load on M4 screw:	110.83	N (tension for screws)
Resultante (force) =	759.35	N (shear load)
Shear load on M4 screws:	94.92	N (shear load / number of screws)
COG of resultant (force):	35.95	mm from rotation pt

Case 2: **acceleration of 424,3 m/s2 acts in horiozontal direction in the Front view to the right.**

Screws for compleet HX

ad. 2.3:

Remark *: Rotation point at right side of the brackets in Front view.

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	40.81	5751.78
HX 2 pipes	0.3218	136.53	40.81	5571.71
HX core	0.5943	252.14	39.66	9999.88
clip left	0.0867	36.78	36.26	1333.78
clip right	0.0867	36.78	36.26	1333.78
2 ThermoSwitch L 2pc	0.0160	6.79	64.56	438.25
2 ThermoSwitch L 2pc	0.0160	6.79	45.00	305.47
2 ThermoSwitch R 2p	0.0160	6.79	25.44	172.69
CO_2- liquid	0.0541	22.95	40.81	936.70
Bracket Left	0.1222	51.85	8.11	420.46
Bracket Right	0.1222	51.85	8.11	420.46
4 Screws L clip M4x10	0.0108	4.58	9.30	42.61
4 Screws R clip M4x10	0.0108	4.58	9.30	42.61
Total load due to acceleration:		759.35 [N]		
			Total moment:	26770 [Nmm]

Equilibrium for screws:

Position (4 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	84.5	4	338
right	4.5	0.2130178	0.9585799
		Total bolt moment:	338.95858 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 78.98 N

Resultante (force) = 759.35 N (shear load)

Shear load on M4 screws: 94.92 N (shear load / number of screws)

COG of resultant (force): 35.25 mm from rotation pt

CONCLUSION MAXIMUM SCREW LOAD ON SCREWS FOR BRACKET

Screws for compleet HX

NB. All screws are in service.

Summary screw load as calculated before;

ad. 2.1:	Maximum tension load on M4 screw:	266.22	N
	Shear load on M4 screws:	0.00	N.
	Torque screw:	TBD	N.mm
ad. 2.2:	Maximum tension load on M4 screw:	110.83	N
	Shear load on M4 screws:	94.92	N.
	Torque screw:	TBD	N.mm
ad. 2.3:	Maximum tension load on M4 screw:	78.98	N
	Shear load on M4 screws:	94.92	N.
	Torque screw:	TBD	N.mm

Conclusion for the determination of the Factor of Safety for the screws which fixate the HX by the clips:

The screw load factors of safety have to be calculated for situation ad. 2.1 and ad. 2.2. Ad. 2.3 is less critical as ad. 2.2.

The screw load factors of safety depends also of;

1) the torque on the screws and friction coëfficients. Torque pre loads the screws
2) the temperature differences in case of different thermal coëfficients of the materials

Overall conclusions:

Most critical screw load is the fixation of the complete HX including brackets on the base plate for an acceleration of 424,3 m/s2 acting in vertical direction upward, normal to base plate.
This is case 2.1:

Maximum work load on the screw =	171.30 N	
Resultante (force due to max. acceleration) =	759.35 N	
COG of resultant (force due to max. acceleration)=	55.56	mm from cantilever point

Material screw:	CRES 316	
Type screw:	.19-32 UNF (10-32 UNF).	(d2=3,853 d1=4,281)
Secure:	By using heli coil MS 21209 F1-20L	
Section area of M4:	12.98 mm2	

Mechanical properties at 20 C from	CRES 316
Ultimate strength:	503 MPa
Yield strength (0.2%):	179 MPa
Modulus of Elasticity:	179270 MPa
Mean linear expansion:	8.50E-06 mm/mm.K

FoS	for	Max. allowable stress
2.5	ultimate	201.2 MPa
1.5	yield	119.3 MPa

Mechanical properties at 100 C from	CRES 316		
Ultimate strength:	443 MPa	88	% of strength 20C *)
Yield strength (0.2%):	165 MPa	92	% of strength 20C *)
Modulus of Elasticity:	158654 MPa	88.5	% of strength 20C *)
Mean linear expansion:	8.80E-06 mm/mm.K (between 20 C and 100C *)		

FoS	for	Max. allowable stress
2.5	ultimate	177 MPa
1.5	yield	110 MPa

*: ref.:MIL-HDBK-5J; p.2-228/229

Factor of Safety analysis: (min. FS $_{\text{on ult}}$ = 2.5, min FS $_{\text{on yield}}$ = 1.5)

Max. ult. load on screw .19-32 UNF made from CRES 316 at 100 degree C = 2298.9 N
Max. yield load on screw .19-32 UNF made from CRES 316 at 100 degree C = 1425.5 N
Conclusion: Yield load situation is determining design.

Pre-load on .10-31 UNF screw may be: 1254.2 N (= 1425,5 - 171,3N)

The screws for the fixation of the clip and the clip strength should be analysed again in document: ***Analysis of clip V3.xls***

On next pages the situation will be analysed if one screw, the highest loaded screw will loose.

Case 1: **(acceleration of 424,3 m/s2 acts in vertical direction upward, normal to base plate)**

One screw lost!

Remark *: Rotation point at right side of right bracket in Right view.

ad. 1.1: **One screw failure!**

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	63.55	8956.77
HX 2 pipes	0.3218	136.53	11.26	1537.31
HX core	0.5943	252.14	46.21	11651.40
clip left	0.0867	36.78	64.50	2372.55
clip right	0.0867	36.78	10.50	386.23
3 ThermoSwi	0.0240	10.18	64.50	656.76
3 ThermoSwi	0.0240	10.18	10.50	106.91
CO_2- liquid	0.0541	22.95	33.80	775.80
Total acceleration load:		646.49 [N]		
		Total moment:		26444 [Nmm]

The influence of the washers is not taken into account in all calculations below. The mass of a washer is very low.

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	69.5	1	69.5
left mid	58.5	1.6834532	98.482014
right mid	15.5	0.5299145	8.2136752
right	4.5	0.1294964	0.5827338
	Total bolt moment:		176.77842 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 149.6 N

Resultante (force) = 646.49 N

COG of resultant (force): 40.90 mm from rotation pt

So, screw loads are:

left	149.6	N
left mid	125.9	N
right mid	33.4	N
right	9.7	N

Conclusion:

Maximum work load on screw by failure: 149.6 N

(Without failure of one screw max. work on screw was: 107.37 N)

Resultante (force) = 646.49 N (tension for screws)

Maximum tension load on M4 screw: **230.40** N. (Max. work load + Resultante / number of screws)

This is only a little bid higher.

See for the calculations of the Factor of Safety document 'Analysis of clip V3.xls'

Case 1: **acceleration of 424,3 m/s2 acts in horiozontal direction in the Right view to the right.**

Remark *: Rotation point at right side of the right bracket in Right view.

One screw lost!

ad. 1.2: **One screw failure!**

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	30.00	4228.22
HX 2 pipes	0.3218	136.53	30.00	4095.85
HX core	0.5943	252.14	28.85	7274.24
clip left	0.0867	36.78	25.45	936.15
clip right	0.0867	36.78	25.45	936.15
4 ThermoSwi	0.0320	13.58	57.93	786.48
2 ThermoSwi	0.0160	6.79	64.08	434.99
CO_2- liquid	0.0541	22.95	28.85	662.18
Total acceleration load:		646.49 [N]		
		Total moment:		19354 [Nmm]

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	69.5	1	69.5
left mid	58.5	1.6834532	98.482014
right mid	15.5	0.5299145	8.2136752
right	4.5	0.1294964	0.5827338
		Total bolt moment:	176.77842 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 109.48 N (tension for screws)

Resultante (force) = 646.49 N (shear for screws)

Maximum tension load on M4 screw: 80.81 N. (Max. work load + Resultante / number of screws)

COG of resultant (force): 29.94 mm from rotation pt

Case 1: **acceleration of 424,3 m/s2 acts in horiozontal direction in the Front view to the right.**

Screw for Clip
One screw lost!

ad. 1.3: Remark *: Rotation point at right side of the brackets in Front view.

One screw failure!

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	30.00	4228.22
HX 2 pipes	0.3218	136.53	30.00	4095.85
HX core	0.5943	252.14	28.85	7274.24
clip left	0.0867	36.78	25.45	936.15
clip right	0.0867	36.78	25.45	936.15
2 ThermoSwi	0.0160	6.79	53.31	361.88
2 ThermoSwi	0.0160	6.79	33.75	229.10
2 ThermoSwi	0.0160	6.79	14.15	96.05
CO_2- liquid	0.0541	22.95	28.85	662.18
Total load due to acceleration:		646.49 [N]		
		Total moment:		18820 [Nmm]

Equilibrium for screws:

Position (4 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]	
left	63	3	189	13
right	4.5	0.2857143	1.2857143	
		Total bolt moment:	190.28571 [Fb.mm]	

Conclusion:

Maximum work load on M4 screw: 98.90 N (tension for screws)

Resultante (force) = 646.49 N

Maximum tension load on M4 screw: 80.81 N. (Max. work load + Resultante / number number of screws)

COG of resultant (force): 29.11 mm from rotation pt

CONCLUSION MAXIMUM SCREW LOAD ON SCREWS FOR CLIP

Screw for Clip
One screw lost!

NB. One screws is not in service.

Summary screw load as calculated before;

ad. 1.1:	Maximum tension load on M4 screw:	230.40	N
	Shear load on M4 screws:	0.00	N.
	Torque screw:	TBD	N.mm
ad. 1.2:	Maximum tension load on M4 screw:	109.48	N
	Shear load on M4 screws:	80.81	N.
	Torque screw:	TBD	N.mm
ad. 1.3:	Maximum tension load on M4 screw:	98.90	N
	Shear load on M4 screws:	80.81	N.
	Torque screw:	TBD	N.mm

Conclusion for the determination of the Factor of Safety for the screws which fixate the HX by the clips:

The screw load factors of safety have to be calculated for situation ad. 1.1 and ad. 1.2. Ad. 1.3 is less critical as ad. 1.2.

The screw load factors of safety depends also of;

1) the torque on the screws and friction coëfficients. Torque pre loads the screws
2) the temperature differences in case of different thermal coëfficients of the materials

Case 2: **(acceleration of 424,3 m/s2 acts in vertical direction upward, normal to base plate)**

ad. 2.1: **One screw failure!**

Screws for compleet HX
One screw lost!

Remark *: Rotation point at right side of right bracket for Right view.

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	63.55	8956.77
HX 2 pipes	0.3218	136.53	11.26	8676.37
HX core	0.5943	252.14	46.21	16023.51
clip left	0.0867	36.78	64.50	2372.55
clip right	0.0867	36.78	10.50	386.23
3 ThermoSwitch L 3pc	0.0240	10.18	64.50	656.76
3 ThermoSwitch R 3pc	0.0240	10.18	10.50	106.91
CO_2- liquid	0.0541	22.95	33.80	775.80
Bracket Left	0.1222	51.85	64.50	3344.01
Bracket Right	0.1222	51.85	10.50	544.37
4 Screws L clip M4x10	0.0108	4.58	64.50	295.54
4 Screws R clip M4x12	0.0108	4.58	10.50	48.11
Total load due to acceleration:		759.35 [N]		
		Total moment:		42187 [Nmm]

Due to the failure of the highest loaded screw the screw at the left side will fail.

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]	
left	69.5	1	69.5	(1 was 2)
left mid	58.5	1.6834532	98.482014	
right mid	15.5	0.5299145	8.2136752	
right	4.5	0.1294964	0.5827338	
		Total bolt moment:	176.77842	[Fb.mm]

So, screw loads are:

left	238.6	N
left mid	200.9	N
right mid	53.2	N
right	15.5	N

Conclusion:

Maximum work load on screw by failure: 238.64 N (tension for screws)

Resultante (force) = 759.35 N (tension for screws)

Maximum tension load on M4 screw: 333.56 N. (Max. work load + Resultante / number of screws)

Without failure of one screw max. work load on screw was: 171.3 N

This is only higher.

See for the calculations of the Factor of Safety document 'Analysis of clip V3.xls'

Case 2: **acceleration of 424,3 m/s2 acts in horiozontal direction in the Right view to the right.**

ad. 2.2: **One screw failure!**

Screws for compleet HX
One screw lost!

Remark *: Rotation point at right side of right bracket for Right view.

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	40.81	5751.78
HX 2 pipes	0.3218	136.53	40.81	5571.71
HX core	0.5943	252.14	39.66	9999.88
clip left	0.0867	36.78	36.26	1333.78
clip right	0.0867	36.78	36.26	1333.78
4 ThermoSwitch L 4pc	0.0320	13.58	68.80	934.06
2 ThermoSwitch R 2p	0.0160	6.79	74.89	508.37
CO_2- liquid	0.0541	22.95	40.81	936.70
Bracket Left	0.1222	51.85	8.11	420.46
Bracket Right	0.1222	51.85	8.11	420.46
4 Screws L clip M4x10	0.0108	4.58	9.30	42.61
4 Screws R clip M4x1	0.0108	4.58	9.30	42.61
Total load due to acceleration:		759.35 [N]		
		Total moment:		27296 [Nmm]

Equilibrium for screws:

Position (2 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	69.5	1	69.5
left mid	58.5	1.6834532	98.482014
right mid	15.5	0.5299145	8.2136752
right	4.5	0.1294964	0.5827338
		Total bolt moment:	176.77842 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 154.41 N

Resultante (force) = 759.35 N (shear for screws)

Shear load on M4 screws: 94.92 N (shear load / number of screws)

COG of resultant (force): 35.95 mm from rotation pt

Without failure of one screw max. work load on screw was: 110.8 N

This is only a little bid higher.

Case 2:

ad. 2.3: **One screw failure!**

Remark *: Rotation point at right side of the brackets in Front view.

Screws for compleet HX
One screw lost!

part	mass [kg]	acceleration load [N]	arm * [mm]	moment [Nmm]
HX 4 pipes	0.3322	140.94	40.81	5751.78
HX 2 pipes	0.3218	136.53	40.81	5571.71
HX core	0.5943	252.14	39.66	9999.88
clip left	0.0867	36.78	36.26	1333.78
clip right	0.0867	36.78	36.26	1333.78
2 ThermoSwitch L 2pc	0.0160	6.79	64.56	438.25
2 ThermoSwitch L 2pc	0.0160	6.79	45.00	305.47
2 ThermoSwitch R 2p	0.0160	6.79	25.44	172.69
CO_2- liquid	0.0541	22.95	40.81	936.70
Bracket Left	0.1222	51.85	8.11	420.46
Bracket Right	0.1222	51.85	8.11	420.46
4 Screws L clip M4x10	0.0108	4.58	9.30	42.61
4 Screws R clip M4x10	0.0108	4.58	9.30	42.61

Total load due to acceleration: 759.35 [N]

Total moment: 26770 [Nmm]

Equilibrium for screws:

Position (4 screws)	arm * [mm]	Fb [ ]	moment [Fb.mm]
left	84.5	3	253.5
right	4.5	0.2130178	0.9585799
		Total bolt moment:	254.45858 [Fb.mm]

Conclusion:

Maximum work load on M4 screw: 105.20 N

Resultante (force) = 759.35 N (shear for screws)

Shear load on M4 screws: 94.92 N (shear load / number of screws)

COG of resultant (force): 35.25 mm

Without failure of one screw max. work load on screw was: 79.0 N

This is only a little bid higher.

CONCLUSION MAXIMUM SCREW LOAD ON SCREWS FOR BRACKET

Screws for compleet HX
One screw lost!

NB. One screws is not in service.

Summary screw load as calculated before;

ad. 2.1:	Maximum tension load on M4 screw:	333.56	N
	Shear load on M4 screws:	0.00	N.
	Torque screw:	TBD	N.mm
ad. 2.2:	Maximum tension load on M4 screw:	154.41	N
	Shear load on M4 screws:	94.92	N.
	Torque screw:	TBD	N.mm
ad. 2.3:	Maximum tension load on M4 screw:	105.20	N
	Shear load on M4 screws:	94.92	N.
	Torque screw:	TBD	N.mm

Conclusion for the determination of the Factor of Safety for the screws which fixate the HX by the bracket:

The screw load factors of safety have to be calculated for situation ad. 2.1 and ad. 2.2. Ad. 2.3 is less critical as ad. 2.2.

The screw load factors of safety depends also of;

1) the torque on the screws and friction coëfficients. Torque pre loads the screws
2) the temperature differences in case of different thermal coëfficients of the materials